A Study of Excess Motor Vehicle Emissions – Causes and Control

Section IV

Evaluation of "Expert Systems" and Test Analyzer System Enhancements for the California Smog Check Program

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Air Resources Board

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1. SUMMARY

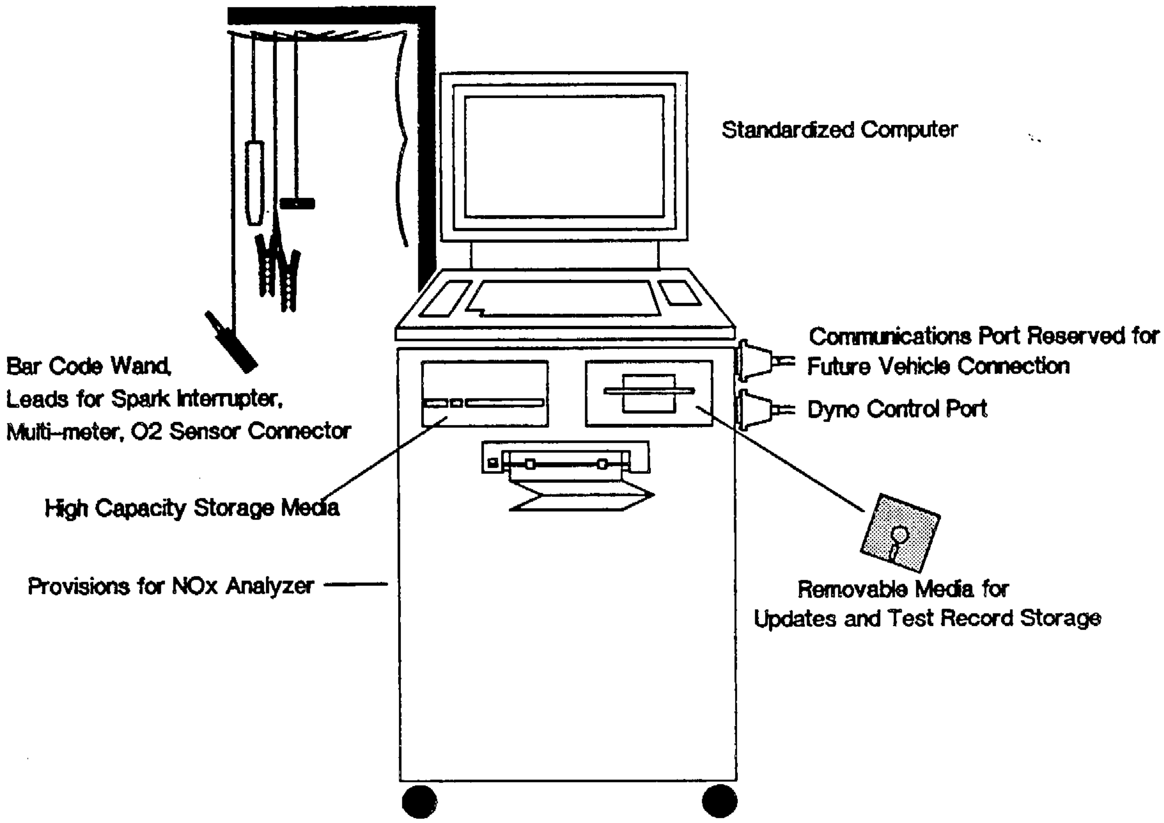
An evaluation of possible Test Analyzer System (TAS) enhancements for the California vehicle inspection and maintenance (Smog Check) program indicates that the effectiveness of the program could be improved through the incorporation of "expert system" software and other TAS changes. Based on specific information available on each vehicle tested, expert system software could guide mechanics to the identification of defective components. Other new TAS features that could improve mechanic performance, especially in conjunction with an expert system, include 1) automated testing of exhaust oxygen sensors and feedback control systems, 2) automated testing of catalyst efficiency, and 3) engine family specific emission standards and inspection procedures. Enforcement could be enhanced through the collection of supplemental information regarding mechanic performance on each vehicle tested.

Although expert systems could be designed to function independently (without affecting the Test Analyzer System), system effectiveness and cost effectiveness would be optimized through the integration with the Test Analyzer System. Because expert system software would need to be periodically updated, it is important for new TASs to be designed to accommodate frequent software and data base modification. Because expert system software development is expected to be expensive, standardization of TAS hardware and software would substantially reduce the cost of program development and maintenance.

Figure 1 is a schematic of a possible 1990s TAS. The new hardware features of the proposed system are identified on the schematic. The proposed new hardware features include a variety of supplemental data leads to be used in conjunction with the current leads for the measurement of engine speed and the exhaust gas analyzer probe. These supplemental data leads could provide for the automated testing of catalyst efficiency, feedback control systems, exhaust oxygen sensors, and a variety of other sensors used on 1980 and later model year vehicles. A bar code reading wand would enable the TAS to read information from the new underhood tuneup labels that ARB regulations will require beginning with the 1990 model year. By adding bar code

Figure 1

Possible 1990s Test Analyzer System



reading capability to the TAS, the accuracy and speed of entering Certificate of Compliance numbers would also be increased. This would greatly facilitate the identification of counterfeit certificates and improperly issued certificates because the TAS could be programmed to accept only certificate numbers within a range purchased by the Smog Check station.

Table 1 provides more detailed information regarding the proposed hardware and software features of the next generation of Test Analyzer Systems. Significant changes from the current generation TAS include a mass storage device capable of holding at least 20 million "bytes" of computer programs and information regarding specific makes and models of vehicles. This is equivalent to about 6,000 pages of printed information. A new floppy disk drive system is proposed which

Table 1

Recommended 1990 TAS Features

------- Hardware -------

- CPU Capable of Using Standardized Operating System
- Minimum RAM Specification (640 Kilobytes)
- High Capacity Data/Program Storage Device (20 Megabytes)
- Standardized Removable Media (3.5" floppy)
- Standardized Communication Ports (2 or 3 RS232 ports)
- O2 Sensor Connector w/internal voltmeter & voltage generator
- Spark Interrupter Lead
- Multi-meter Leads
- Bar Code Wand
- Provision for NOx Analyzer

------- Software -------

- Standardized Operating System
- Standardized Programming Language (compiled)
- Standardized Data File Formats
- Keyboard Input Error Checking/Flagging
- Engine Family Specific Emissions/Dilution/RPM Standards
- Engine Family Specific Preconditioning Procedures
- Engine Family Specific Supplemental Inspection Procedures
- Automatic O2 Sensor, Feedback System, and Catalyst Checks
- Phase I Expert System Programming
- Revised and Expanded Repair Action Categories

has greater storage capacity than the cassette tape recorder systems used on current TASs. It is also proposed that the new system be equipped with auxiliary communication ports reserved for possible future use in dynamometer testing and direct connection with the onboard computers of vehicles under test. Provisions for the addition of NOx analyzers are another feature recommended to facilitate future use of the analyzer with loaded mode testing.

Table 1 also lists several software enhancements proposed for the new TAS. In conjunction with the new hardware features, the next generation TAS could provide automated testing of certain critical components including oxygen sensors, feedback control systems, and catalysts. Diagnostic procedures to test these components have been developed under previous ARB contracts. However, use of the procedures currently requires several steps to be followed precisely while a variety of exhaust emission, engine speed, and voltage measurements are being simultaneously made by the test mechanic. With the hardware and software changes proposed for the new TAS, these diagnostic procedures can be performed automatically after the mechanic has connected electrical leads to the vehicle.

Also listed in Table 1 is "Engine Family Specific Inspection Procedures". In conjunction with expert system software, this is one of the most powerful features of the proposed new system. The specified 20 Mbyte storage medium is large enough that it will be possible to utilize vehicle-specific information regarding recall campaigns, commonly occurring defects, onboard computer code translation, and optimum "fault trees" for diagnosing problems. Vehicle-specific information can also be utilized to determine whether idle speeds have been set properly and whether the amount of exhaust dilution is in the expected range. Vehicle-specific information will also facilitate the use of alternative testing and preconditioning procedures to avoid "pattern failure" problems.

A number of software changes have also been recommended for visual inspection procedures. As shown in Table 2, it is proposed to retain most of the visual inspection procedures currently used in "BAR'84" analyzers. Supplemental inspections are recommended based on the commonly occurring defects that have been identified in roadside inspection programs, ARB surveillance programs, and the I/M Evaluation Program. These supplemental procedures include more specific inspection requirements for air injection systems, the identification of failure codes obtained from onboard diagnostic systems, and the identification of recall campaigns that have been completed (as evidenced by the presence of an underhood sticker).

At the bottom of Table 2, it is indicated that two new categories of response are suggested. Currently, mechanics enter the results of each visual inspection as "pass", "disconnected", "modified", "missing", or "not applicable". No entry is currently provided for components which are installed but malfunctioning. Addition of the "malfunctioning" response is important because many defects observed during previous testing programs do not fit into any other category.

Table 2

Recommended Visual Inspection Categories For the 1990s Test Analyzer System

------- Carryover From Current TAS -------

- PCV System
- Thermostatic Air Cleaner
- Fuel Evaporative Controls
- Oxidation Catalyst
- 3-Way Catalyst
- Exhaust Gas Recirculation
- Ignition Spark Controls
- Carburetor or Fuel Injection
- Other

------- New Inspection Categories -------

- Air Injection Pump
- Air Pump Belt
- Pulse Air Reed Valves
- Air Injection Plumbing
- Air Injection Diverter Valve
- Exhaust Manifold
- Intake Manifold
- O2 Sensor Connection and Warning Light
- Wiring of Other Sensors/Switches
- Vacuum Line Connections to Sensors/Switches
- Computer Fault Codes (Up To 9 Entries)
- Recall Completion Verification Number (Up To 4 Entries)

Note: New Failure Codes Added for "Malfunctions" and "Vacuum Line" Problems

The other proposed new failure code is for vacuum line defects associated with the inspected component. Although some mechanics may already check the vacuum lines connected to components included on the visual inspection list, the presence of a specific prompt for vacuum line inspection results will encourage the performance of this check and provide more detailed information to BAR on the manner in which systems are actually failing in customer service.

Table 3 summarizes the functional tests that are proposed for the 1990s TAS. Currently, there are three functional tests which may be activated in BAR'84 analyzers. These are "engine warning lights", "ignition timing", and "EGR". The engine warning light test has been replaced by several new entries in the visual inspection category. The ignition timing and EGR tests are proposed to be retained. Of the functional tests that would be manually performed, a fillpipe lead restrictor test is added. (BAR has administratively required this test to be performed under the "visual" inspection of the fillpipe restrictor under the current program.) Also added is a functional test of the PCV system (to ensure that the PCV valve is not plugged).

Table 3

Manual and Automated Functional Checks Proposed For the 1990s Test Analyzer System

——— Manual Function Checks ———

- PCV System
- Fillpipe Lead Restrictor
- Exhaust Gas Recirculation System
- Ignition Timing

——— Automated Functional Checks ———

- O2 Sensor Test (voltage ouput)
- Feedback Control System Test (automated version of finger touch)
- Catalyst Efficiency Test (automated version of plug disconnect)
- Supplemental Sensor Tests (Engine Family Specific)

Table 3 also shows that several new functional tests are added under the heading of "automated functional tests". These include the oxygen sensor test, the feedback control system test, and the catalyst efficiency test mentioned earlier. Oxygen sensor function would be monitored while the feedback control system is driven to the rich and lean limits by alternatively applying zero and 1 volt to the oxygen sensor leads while the voltage output of the sensor is monitored. Simultaneous measurement of exhaust emissions could determine whether the feedback control system is responding properly to the input voltage. The catalyst test would involve the measurement of exhaust emissions while the voltage to one spark plug is interrupted. The amount of emissions increase would determine whether the catalyst is efficiently converting HC and CO emissions to carbon dioxide and water vapor. Because of the potential for inducing defects through the performance of functional inspections that involve the disconnection of wires, it may be advisable to implement oxygen sensor and catalyst checks only for vehicles which either fail the tailpipe standards or have engine warning lights illuminated. Supplemental sensor tests would be vehicle-specific and would generally involve voltage and resistance measurements across the terminals of various sensors.

Table 4 lists the repair action categories that are proposed for the 1990s TAS. Timing adjustment and air/fuel ratio adjustment categories currently used would be retained. The more generic categories of "misfire", "crankcase", "fuel evaporative controls", and "EGR" would be replaced by a much larger number of more detailed repair action categories. Ten major categories are proposed, each covering a major portion of the emissions control system. Mechanics would be prompted to enter information for a variety of subcategories whenever it is indicated that repairs have been made in any of the main categories. In all, fifty-four different categories of repair action are suggested, compared to the seven categories which are currently used. This would provide an enormous increase in detail which BAR could use to better determine how vehicles are being repaired under the program. This level of detail would also be helpful in determining when a mechanic is making repairs that are unreasonable under specific circumstances.

In order to implement all of the Test Analyzer System enhancements considered, it does not appear feasible to retrofit existing TAS machines. Although some components in the current analyzers could be salvaged (e.g., emission analyzers, printers, CRTs, etc.), it is likely that all-new systems would generally be required. It has been estimated that the new systems would cost about $1,000 more than the BAR'84 specification analyzers. Amortizing this cost over a five-year period (assuming a 10% cost of funds) the average increase in inspection costs would be about $1.50 per test. This is an extremely conservative (i.e., high) estimate because it is based on the assumption that existing TAS analyzers would otherwise not have to be replaced. By the time a new TAS could be ready for the market (about 1992), many of the current systems would have been in service for eight years and would be ready for replacement.

Table 4

Recommended Repair Action Categories For the 1990s Test Analyzer System

——— Carryover From Current TAS ———

- Timing Adjustment
- Air/Fuel Ratio Adjustment

——— New Repair Categories ———

- Ignition System Repair (5 Subcategories)
- Intake System Repair (12 subcategories)
- PCV System Repair (4 Subcategories)
- Evaporative Emissions Control System Repair (3 Subcategories)
- EGR System Repair (4 Subcategories)
- Repair of Sensors and Switches (9 Subcategories)
- Fillpipe or Exhaust System Repair (4 Subcategories)
- Air Injection System Repair (7 Subcategories)
- Computer Replacement
- Miscellaneous Repairs (5 Subcategories)

——— Proposed For Deletion ———

- Misfire
- Crankcase (generic)
- Fuel Evaporative Controls (generic)
- Exhaust Controls (generic)
- EGR (generic)

Total Number of Current Categories: 7

Total Number of Proposed Categories: 54

The potential emission benefits of enhanced Test Analyzer Systems have also been conservatively estimated. It is estimated that the minimum incremental benefits would be an additional 4.8 percentage point reduction in hydrocarbon emissions, a 2.5 percentage point reduction in carbon monoxide emissions, and a 3.2 percentage point reduction in oxides of nitrogen emissions. Even accounting for the reduction in vehicle emissions that is projected to occur between now and the year 2000, the cost per pound of hydrocarbon plus NOx control is estimated to be as low as $1.59. This is competitive with other emission control measures.

Of the available implementation options, BAR-sponsored development of the expert system software to be incorporated in the 1990s TAS is strongly recommended. Vendor-specific software of this nature could lead to significant inconsistencies in the manner in which failures are diagnosed. One basic expert systems program would also be much more economic to maintain. For the same reason, it is recommended that BAR be involved in the development of the software that will be used to control the basic operation of the Test Analyzer Systems. To the extent possible, it would be desirable for the software used in all systems to be identical.

With a high degree of consistency in software and removable media, it will be possible for the next generation of TASs to be periodically updated at the lowest possible cost. Because the data needs of expert systems are substantial, the economic feasibility of the expert systems approach is dependent on this approach.

Initial software development costs are estimated to be in the range of $1 million. However, periodic updates could be performed at relatively modest costs. This is especially true if ARB would require vehicle manufacturers to routinely supply data in a consistent format regarding the characteristics of all vehicles certified for sale in California.

The development and implementation of the proposed Test Analyzer System enhancements could represent a major step towards reversing the disturbing trend in the effectiveness of diagnosis and repair of emissions-related defects. (A recent survey by California State University, San Bernardino, indicates that Smog Check mechanics are less able to diagnose problems with 1980 and later model vehicles.) As more vehicles are equipped with sophisticated computer-controlled systems, the features possible in an enhanced analyzer are becoming more important.

2. INTRODUCTION

An investigation of Expert Systems was Task Number 3 of the Scope of Work under a contract with the California Air Resources Board for "A Study of Excess Motor Vehicle Emissions - Causes and Control" (ARB Contract No. A5-188-32). The principal objective of the task was to perform a "scoping study" of how the accuracy of inspections and repairs performed under the Smog Check program could be improved through the use of so-called "expert systems".

In this study, an "expert system" is defined to be a computer program which models the decision-making process of a human expert. (As clarified later in the report, the expert system concept addressed in this study should not be confused with "artificial intelligence".) Under the Smog Check program, an expert system could provide the mechanic with recommended inspection and diagnostic procedures based on detailed information available for the particular make and model of vehicle under evaluation. The knowledge contained in the expert system could be derived from many different individuals who specialize in different vehicles and problems. By aiding in failure diagnosis, expert systems could increase the emission reductions from the smog check program through improved repair quality. Although the use of expert systems would add to the equipment cost associated with the operation of a Smog Check station, the cost for diagnosis and repairs could be reduced by shortening the repair time and eliminating costs associated with replacing components that are not defective.

To accomplish the overall objective of Task 3, the following subtasks were outlined in the scope of work:

- review and summary of failure mode information;
- review and summary of diagnostic and repair procedures;
- survey of available diagnostic equipment;
- evaluation of system concept options;
- evaluation of data acquisition options;
- cost, benefit, and leadtime analysis; and
- development of implementation options.

Under Task 9 of the contract, subtask 9.e. requires an evaluation of "Test Equipment Changes". Under this subtask, Sierra is required to work with ARB staff and the 1990's Subcommittee of the I/M Review Committee and provide recommendations and support related to the development of improved test equipment for future use in Smog Check stations. In response to the requirements of subtask 9.e., the integration of expert systems with other Test Analyzer System changes is also addressed in this report.

Although expert systems can be extremely complex and sophisticated, the purpose of this study was to investigate a system for use in the "typical" automotive repair facility participating in the Smog Check program. As such, the focus was on a system that could address only the most significant and commonly occurring emissions-related problems. Much greater sophistication would be used in expert systems designed for specialized applications like Referee facilities or franchised dealerships that specialize in a particular car line.

Following this introductory section, Section 3 summarizes the causes of excess emissions from vehicles in customer service. The information provided in Section 3 provides a perspective on the nature of the emissions-related defects that need to be addressed through the application of enhancements to the Test Analyzer Systems used in the Smog Check program.

Section 4 provides an overview of the concept behind computer-assisted problem diagnosis with expert system software. The section contains a description of a functioning expert system that has been developed for a non-emissions-related automotive service application. How such a system could be modified for use in the Smog Check program is also discussed. Various diagnostic tests that could be integrated with expert systems software are presented through a review of the capabilities of several diagnostic analyzers already used in some Smog Check stations. Finally, Section 4 summarizes a brief survey of service industry reactions to available advanced diagnostic systems.

Section 5 outlines a development concept and implementation options for expert system software for the Smog Check program. A hypothetical expert system concept for the Smog Check program is presented. The relative advantages and disadvantages of centralized and decentralized expert systems are addressed. Finally, the possible data acquisition and system development options are presented.

Section 6 provides a summary of our conclusions regarding the modifications that should be included in the next generation of Test Analyzer Systems to incorporate expert system software and other enhancements. The level of detail provided is intended to serve as a recommendation to the Bureau of Automotive Repair for the 1990s Test Analyzer System specification.

Section 7 presents an analysis of the potential emissions benefits and cost effectiveness of a modified Test Analyzer System incorporating expert system software.

The Appendix to the report contains the detailed results of the survey of diagnostic equipment users.

3. CAUSES OF EXCESS EMISSIONS

Since the purpose of enhancements to the Test Analyzer System (including the addition of expert systems software) would be to increase the detection and repair of emissions-related defects, the nature of the defects that contribute to excess emissions is an important consideration in the development of analyzer enhancements. Based on two recent studies funded by ARB, the nature of defects which contribute to excess emissions have been analyzed in some detail. One of these studies involved the diagnosis of defects contained in a sample of late-model vehicles equipped with fuel injection systems and 3-way catalysts.* A less detailed but more broadly based evaluation of the defects which contribute to excess emissions was performed under the I/M Evaluation Program.†

In the California fuel-injected vehicle study (referred to herein as the "58 Car Study"), Radian procured fuel-injected vehicles with excess emissions and repaired them. Candidate vehicles were identified by searching California Bureau of Automotive Repair (BAR) data for vehicles receiving cost waivers.

Late Model, Fuel-Injected Vehicles

The test fleet evaluated under the 58 Car Study was dominated by 1980 to 1982 model year vehicles and included more mechanical and throttle body fuel-injected vehicles than electronic multipoint fuel-injected vehicles. Since the test fleet had already failed the Smog Check and received waivers, the vehicles may represent those with the most serious emissions problems. The results of the 58 Car Study identify the reasons for excess emissions from fuel-injected vehicles and reasons for the excess emissions from waiver vehicles. However, only 14 of the 51 vehicles that underwent the full test plan had sophisticated onboard diagnostic (OBD) systems. They may not therefore represent the behavior of fuel-injected vehicles currently being sold in California.

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* R. Klausmeier, et al, Radian Corporation study of excess emissions from multipoint fuel-injected vehicles for the Air Resources Board (final report not yet published).

† "Evaluation of the California Smog Check Program, Technical Appendix," Sierra Research, Inc., April 1987.

Test vehicles underwent the full Federal Test Procedure (FTP) for exhaust emissions upon acceptance. They were then subjected to a generic diagnostic and repair procedure. First, a detailed inspection was performed which included in most cases functional checks of key emission-related components. Repairs generally were performed in the following order:

- Basic restorative maintenance (for example, ignition system or induction system problems),
- Electronic control system repairs (This often consists of either reconnecting or replacing the oxygen sensor. Basic engine parameters were readjusted if the replacement of the component could affect them.), and
- Catalyst activity test and replacement in some cases.

After each repair step most vehicles were tested by the hot transient portion of the FTP. If the hot transient results indicated that the problem was likely to have been fixed, the vehicle was subjected to a full FTP prior to being released.

The primary goal of the California fuel-injected vehicle study was to identify causes of excess emissions. Table 5 shows the most prevalent problems found in the test fleet. As indicated, most of the vehicles had problems with the oxygen sensor. About 80 percent of the vehicles required replacement of the oxygen sensor and about 10 percent of the vehicles had disconnected oxygen sensors. As Table 5 shows, in two-thirds of the cases repairs to the oxygen sensor significantly reduced HC and CO emissions, and in slightly less than half of the cases repairs significantly reduced NOx emissions.

Another significant problem found in the fleet was catalytic converter degradation. About 30 percent of the vehicles tested showed severe loss of catalytic converter efficiency, as indicated by the loaded mode catalyst activity test. These results may suggest that many fuel-injected vehicles may have bad catalysts, but more data are needed to determine the extent of the catalytic converter problem.

EGR system problems were prevalent in vehicles equipped with EGR. About a third of the vehicles had maladjusted idle mixtures, but the emissions impact of these maladjustments generally was lower than problems in other components, such as the oxygen sensor. Similarly, about a third of the vehicles had problems in the ignition system, but again the emissions impact of these problems was minor.

To provide a better indication of the fleet emissions impact of different types of problems, Radian tabulated the specific types of repairs that resulted in the greatest emission reductions. Table 6 shows the repairs that were responsible for over 80 percent of the HC reductions. As shown, reconnection or replacement of the oxygen sensor accounted for about 50 percent of the overall HC emission

Table 5

PROBLEMS IN FUEL INJECTED VEHICLES

REPAIR ITEM	PERCENT FOUND MALFUNCTIONING *	PERCENT THAT REPAIR REDUCED EMISSIONS HC	CO	NOX
OXYGEN SENSOR	90%	67%	69%	44%
CATALYTIC CONVERTER	29%	100%	100%	100%
EGR	41%	11%	22%	67%
IDLE CO	41%	39%	45%	34%
SPARK PLUGS & WIRES	31%	41%	53%	41%
COOLANT TEMP SENSOR	7%	100%	50%	0%
TIMING	37%	40%	40%	100%

* Among vehicles equipped with device

Table 6

REPAIRS RESPONSIBLE FOR OVER 80% OF HC EMISSION REDUCTIONS

REPAIR ITEM	PERCENT OF FLEET	PERCENT OF TOTAL HC REDUCTION
OXYGEN SENSOR REPLACEMENT	26%	31%
RECONNECT OXYGEN SENSOR	16%	17%
REPLACE OXYGEN SENSOR & CATALYST	2%	12%
REPLACE OX /AIR FLOW SENSOR, BCDD	2%	8%
REPLACE OX SENSOR & TUNE-UP ITEMS	2%	7%
REPLACE CATALYST	4%	6%
	52%	81%

reductions. Furthermore, of the six types of repairs shown on the table, five involved the oxygen sensor.

Repairs involving replacement of the catalytic converter also accounted for a significant percentage of the overall HC emission reductions. It must be noted that 14 vehicles were found with bad catalysts, but only four received new catalysts. Consequently, Table 6 underestimates the overall impact of catalytic converter degradation in the test fleet.

Table 7 shows repairs responsible for over 80 percent of the CO emission reductions. As indicated, the oxygen sensor was the major component responsible for excess CO emissions. About two-thirds of the CO emission reductions occurred strictly from replacing or reconnecting the oxygen sensor, and the remaining combinations that significantly reduced CO emissions still involved the oxygen sensor along with other components.

Table 7

REPAIRS RESPONSIBLE FOR OVER 80% OF CO EMISSION REDUCTIONS

REPAIR ITEM	PERCENT OF FLEET	PERCENT OF TOTAL CO REDUCTION
REPLACE OXYGEN SENSOR	22%	44%
RECONNECT OXYGEN SENSOR	12%	20%
REPLACE OX SENSOR & AIR FLOW SENSOR	2%	14%
REPLACE OX SENSOR / AIR FUEL ADJUST	2%	9%
	38%	87%

The analysis of NOx emission reductions looked at vehicles with EGR separately from vehicles without EGR. Table 8 shows repairs responsible for over 80 percent of the NOx emission reductions for vehicles without EGR. As indicated, a wide variety of problems contributed to excess NOx emissions. Unlike the causes of excess HC and CO where the oxygen sensor emerged as the primary component, several different components showed up as being important for NOx control. But the oxygen sensor was the most important component, and its replacement or reconnection was responsible for 32 percent of the overall NOx emission reductions. The catalytic converter was another significant component. Again, had the catalytic converter been replaced when necessary, repairs involving the catalytic converter would have accounted for a much greater portion of the total NOx emission reductions. Other items such as tune-up related components and vacuum leaks also contributed to excess NOx emissions from vehicles without EGR systems.

Table 8

REPAIRS RESPONSIBLE FOR OVER 80% OF NOX EMISSION REDUCTIONS VEHICLES WITHOUT EGR

REPAIR ITEM	PERCENT OF FLEET	PERCENT OF TOTAL NOX REDUCTION
RECONNECT OX SENSOR, TUNE UP AND FIX VACUUM LEAKS	3%	24%
REPLACE OXYGEN SENSOR	21%	17%
RECONNECT OXYGEN SENSOR	10%	15%
REPLACE CATALYST	7%	12%
TUNE UP & FIX VACUUM LEAKS	3%	12%
	44%	80%

For vehicles without EGR, only two combinations showed up as being responsible for most of the emission reductions:

- Repair EGR, replace catalyst and ECM, and
- Repair EGR alone.

As Table 9 shows, repairs to 15 percent of the vehicles accounted for over 90 percent of the NOx emission reductions.

As mentioned earlier, the catalytic converter was identified as a major cause of excess emissions. Figure 2 shows the effect of repairs to two groups of vehicles: those with good catalysts and those with bad catalysts. As shown, minimal reductions in HC and NOx occurred for vehicles with bad catalysts. On the other hand, CO emissions were significantly reduced from both groups of vehicles. Apparently the catalytic converter is more important to the control of HC and NOx emissions than CO emissions. When the total quantity of excess emissions was tabulated, a majority of the excess remaining in the fleet after repairs was from a minority of vehicles with bad catalysts.

Table 9

REPAIRS RESPONSIBLE FOR OVER 80% OF NOX EMISSION REDUCTIONS
VEHICLES WITH EGR

REPAIR ITEM	PERCENT OF FLEET	PERCENT OF TOTAL NOX REDUCTION
REPLACE CATALYST & ECM, REPAIR EGR	5%	58%
REPAIR EGR	10%	32%
	15%	90%

Figure 2

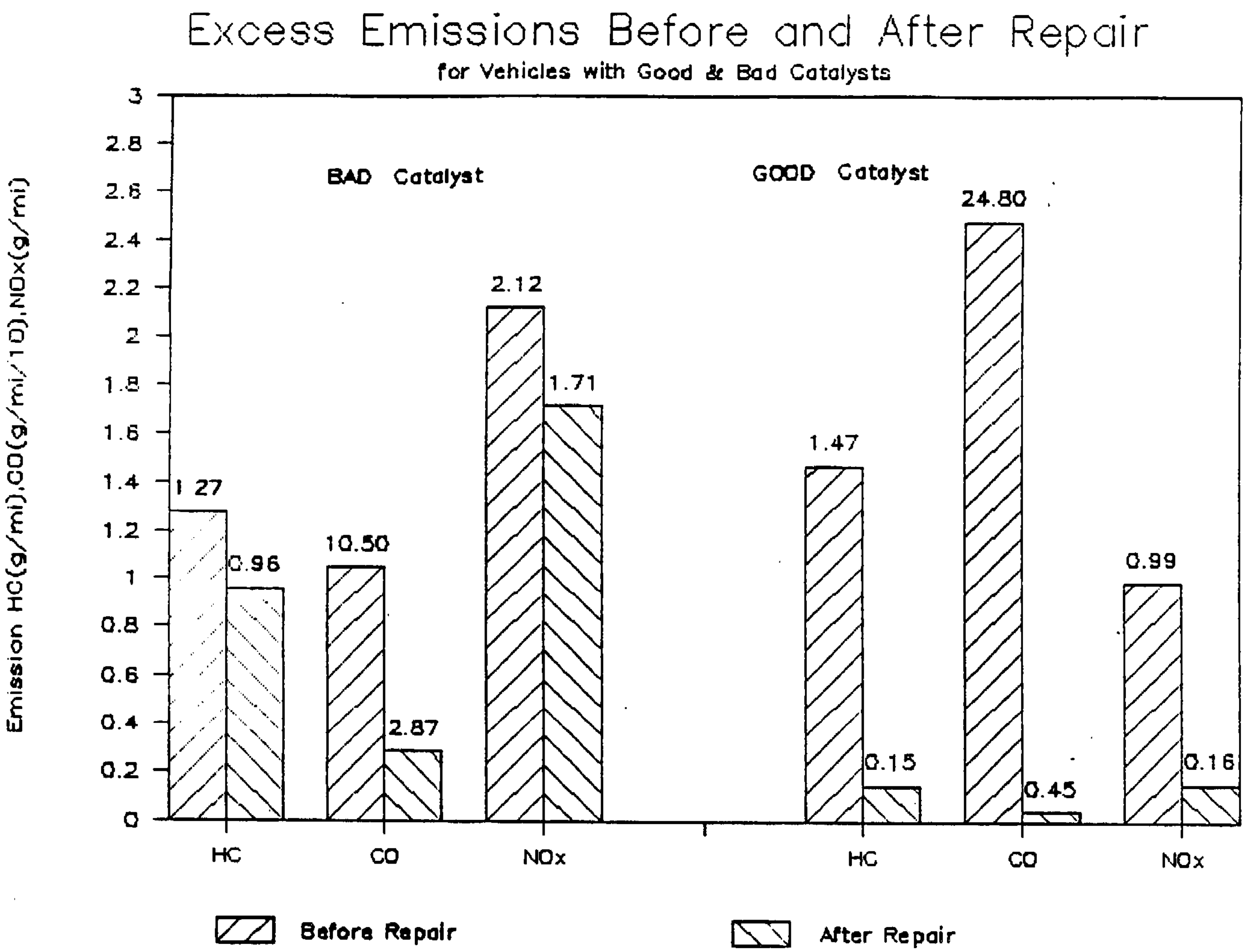


Table 10 summarizes the causes of excess emissions. The oxygen sensor emerged as the most important component for the control of HC and CO emissions, and for vehicles without EGR systems, the control of NOx. The catalytic converter ranked second in importance in the control of HC emissions, first in control of NOx for vehicles with EGR, and second in control of NOx for vehicles without EGR. The EGR system in vehicles so equipped obviously is important.

Table 10

SUMMARY OF CAUSES OF EXCESS EMISSIONS

REPAIR ITEM	HC	CO	NOX WITH EGR	NOX WITHOUT EGR
OXYGEN SENSOR	1	1	-	1
CATALYST	2	-	1	2
OTHER THREE-WAY SENSORS	3 *	2 *	-	-
TUNE UP ITEMS	3 *	-	-	3
AIR FUEL ADJUST	-	2 *	-	4
VACUUM LEAKS	-	-	-	3
EGR	-	-	2	-

* Much lower impact than higher ranked problems.

Older Vehicles

Sierra's analysis of the causes of excess emissions in older vehicles indicates that "tuneup" items are much more significant. Based on the I/M Evaluation Program, for vehicles that received the greatest improvements, some trends were apparent. The following types of repairs were the most significant in terms of emissions benefits:

Post-'79 Models	'75-'79 Models	Pre-'75 Models
- replace/reconnect O2 Sensor; - replace defective ignition components; - replace defective spark plugs and plug wires; - replace/reconnect vacuum lines	- adjust A/F ratio; - correct misfires; - replace emissions components; - repair vacuum leaks	- correct misfires; - connect vacuum lines; - adjust A/F ratio; - adjust timing; - carb rebuild

Ignition system defects which cause misfire problems are a consistent source of excess emissions in pre-1980 models. Disconnected or defective vacuum lines are another significant problem. Idle air/fuel ratio adjustments were found to be another common defect. Finally, the higher tampering rate for older vehicles and the existence of component defects result in the replacement of emissions control components being a significant means of reducing excess emissions.

To summarize, the specific types of defects in older vehicles that were frequently observed during the I/M Evaluation program included:

- vacuum hoses leaking or disconnected,
- air injection plumbing leaks,
- missing air pump belts,
- defective pulse air valves,
- defective sensors (especially TVS*),
- defective spark plug wires, and
- fouled spark plugs.

Because 1980 and later model vehicles do not have readily adjustable idle air/fuel ratios, improper adjustments of air/fuel ratio may not become a problem as these vehicles grow older. Other problems identified with older vehicles (ignition defects, vacuum line defects, and tampering) will probably occur with greater frequency as the 1980 and later model vehicles accumulate more mileage.

* Thermal Vacuum Switch

4. COMPUTER-ASSISTED PROBLEM DIAGNOSIS

The term "expert system" describes a computer-based system which models the decision-making process of a human expert. Expert systems attempt to capture in computer code the knowledge and informal rules of thumb gained from experience by human experts. This information is formatted in a manner to simulate the process the expert uses to solve particular problems. Expert systems are becoming increasingly important in the application of computer resources to automotive defect diagnosis as engine and emission control systems become increasingly complicated. It is much more difficult for a mechanic to diagnose faults in late-model vehicles due to this increased complexity.

Expert systems differ from conventional computer programs in several ways. One important difference is that the knowledge base (data base of expert solutions or decision-making) is a separate entity of the program and can be revised and expanded as new knowledge is acquired. "Artificial Intelligence" is the term used to describe knowledge base expansion through analysis of data entered by the operator. This approach requires consistently high-quality data input which could not be expected in all environments and is not considered a feasible or necessary element of an expert system for use in general-purpose automotive repair facilities. Expert systems allow uncertainty to be considered in the modeling of expert behavior and they can explain the line of reasoning leading to recommended actions.

As discussed in Section 3, major causes of excess emissions in new technology vehicles are malfunctions of the oxygen sensor and the catalytic converter. An expert system could provide vehicle-specific inspection procedures for these and other components. In addition, the expert system could assist in identifying vehicles subject to recalls or in performing special exhaust emission tests to avoid improper identification of "pattern failures". Once a vehicle has been identified as failing the smog check, an expert system also could assist in repairs by providing mechanics with recommended diagnostic procedures for specific types of problems, and with interpretation of the results of the diagnosis. Furthermore, an expert system would perform consistently and rapidly, without human error. Another use is to provide Smog Check mechanics with the collective advice of several expert diagnosticians during repairs.

An Example of the Use of an Expert System

An example will help illustrate how an expert system could be used in the Smog Check Program. Radian recently developed an expert system to troubleshoot the cooling system in Diesel engines manufactured by Cummins Engine Company. This expert system, which has been named MARV (after a cooling system expert named Marv Lawson), contains several features that would be desirable in an expert system to assist in inspection or repair of motor vehicles. The following session with MARV provides an example of the use of expert systems.

The screens shown below represent actual graphics that appear on a CRT screen when MARV is run. MARV requests the user to answer several questions prior to giving advice. Most of the time, responses to the questions are made by moving a cursor up or down, or side to side, and hitting the "Return" key. Sometimes, numerical data are required and must be keyed in.

The first screen that appears is shown below:

Screen 1

```
Is this a new run ?

  [new]
  repeat

  help
  menu access
```

In the above screen, MARV is asking if this is a new run or a repeat run. If it is a repeat run, a file name will be requested. This is done to prevent the situation where a mechanic must completely redo the session to return to where he left off. In this case, this is a new run. The same situation would apply to vehicle repairs or inspections. If a mechanic is working on several vehicles or performing several inspections at the same time, he does not want to repeat the previous session for a given vehicle. Instead, the mechanic would want to start where he left off last. For example, if the mechanic completed the emission test but not the tampering inspection or the oxygen sensor check, he would only want to return to that portion.

The next instruction that MARV gives is for the mechanic to specify the engine type. This is shown on Screen 2.

Screen 2

```
Please specify the engine type.

  [BCIV]
  NT444

  menu access
```

Two engines are covered by this expert system: The Big Cam IV (BCIV) and the NT 444. In the Smog Check Program, it is likely that several questions would be asked to pinpoint the engine type -- model year, make, CID, and possibly the engine family, unless bar codes are available. Depending on how the expert system software is integrated with the rest of the software used in a Test Analyzer System, sufficient information may already have been stored in computer memory to determine the type of engine under test. However, an expert system could minimize the questions asked to determine engine type. For example, if a particular manufacturer only has one engine family per combination of cubic inch displacement and model year then it would not be necessary to prompt the user to input supplemental information regarding the specific engine family.

Next, the expert system seeks information on the general type of problem. In the cooling system example, the options are "overheating", "overcooling", "coolant loss", and "contamination". The cursor falls on the most likely response; it must be moved by the arrow keys to other responses. Most of the problems encountered in the field are overheating, so the cursor falls at the overheating line. In the case of an expert system for Smog Check program, the input requested from the mechanic would include previous tailpipe emission levels and visual/functional inspection results. (Codes produced by onboard diagnostic systems would be an important element of the information input to the program.) If the initial inspection was previously performed using the same TAS, this information could be obtained directly from information stored on disk.

Screen 3

```
Please specify the problem.

  overheating
  overcooling
  coolant_loss
  contamination

  menu access
```

The next screen asks for more information about the overheating problem. This information is used to prioritize the diagnostic steps.

Screen 4

```
How would you describe the overheating
problem ?

  hard_pull
  light_pull
  spiking
  after_system_fill
  not_known

  menu access
```

MARV was designed to be used by service experts over the phone. The problems they solve tend to be more difficult, since a mechanic would not be phoning in if he could easily fix the problem. The most common problem these people address is overheating under "hard pull" conditions, i.e., high power/heavy load conditions. Other conditions include overheating under light pull, spiking (a sudden increase in temperature followed by a decrease), and overheating after new coolant has been added. Sometimes the mechanic does not know under what conditions overheating occurs, so a "not known" category is provided.

Prior to getting into detailed advice, the expert system asks the mechanic to assure that basic cooling system problems do not exist.

Screen 5

```
Have you checked the following things ?

 1. Coolant, additive, & antifreeze levels
 2. External coolant leaks
 3. Fan drive & water pump belt tension
 4. Fan & fan shroud
 5. Radiator cap, fins, covers & hoses
 6. Proper water pump
 7. Oil level (not too high)
 8. Overfueling

 [yes]
  no

  menu access
```

In the Smog Check program, a similar checklist could be used for vehicle repairs based upon the type of vehicle, the emission levels, and the onboard computer diagnostic codes. The checklist could be model-specific and could include information related to problems known to be significant for the particular model being tested, including problems related to pattern failures. For example, the expert system may request the inspector to measure emissions on Ford model vehicles after the engine has been turned off and restarted.

After going through system prechecks, MARV asks the mechanic if he has the "OAC" troubleshooting kit.

Screen 6

```
Do you have the OAC troubleshooting kit ?

 [yes]
  no

  menu access
```

Recommended diagnosis depends on whether or not the mechanic has the kit. For example, some of the following diagnostic steps are not requested if the mechanic does not have the kit, because it is time-consuming to obtain the data without the kit. Although vehicle inspections will utilize standardized equipment, repairs are likely to utilize a variety of equipment. Information on the type of equipment will help the expert system optimize diagnostic procedures. For example, for repairs performed in franchised dealerships, the expert system could capitalize on information that may be obtained only from the use of specialized equipment supplied by the vehicle manufacturer.

MARV then asks the mechanic to assure that the temperature gauge is accurate. Many cooling system problems can be traced to inaccurate temperature gauges, and not real problems of the system. The same case can occur during an inspection or repair. During an inspection process, inadequate analyzer quality control or improper vehicle conditioning may result in inaccurate readings.

The menu at the top of Screen 7 shows three utilities: Run, Quit, and Backup. "Run" re-executes the program and "Quit" stops the program. With appropriate responses to later questions the mechanic can save the current session in a file. "Backup" allows you to return to the previous question. This feature will be very useful in vehicle repair, by allowing the mechanic to change previous responses.

Screen 7

```
Run        R
Quit       Q
Backup     B
```

```
The block pressure test requires taking
pressure readings and other actions at
various temperatures.

The cab temperature gauge should be within
+/- 5 degrees of the test kit's, and the cab
gauge's red line should be at least 212 F.

 [ok]
  bad

  help
  menu access
```

Next, MARV requests that the thermostat housing pressure be measured.

Screen 8

```
The thermost housing pressure is being checked now so
the engine doesn't have to cool down to check it later.

Turn the lower valve on the test kit to 'housing', and
the upper to 'block pressure'.

Before the coolant temperature reaches 66 C [150 F], at
high idle, what is the thermostat housing pressure ?

 34

  [continue]    reenter    help    menu access
```

Had the mechanic answered "no" to the question, "Do you have the OAC trouble-shooting kit?", this question would not be asked. However, because the answer to the question was "yes," it is being asked to avoid the situation where the engine has to cool down to obtain these readings later. Similarly, the following question asks for measurement of the block pressure before the coolant reaches 150°F.

Screen 9

```
What is the block pressure before 66 C [150 F] ?

 33

  [continue]   reenter    help    menu access
```

As the engine warms up, the mechanic is asked to note the thermostat opening temperature.

Screen 10

```
What is the thermostat opening tempera-
ture in degrees F ?

  [170_to_180]
   below_170
   above_180

   help
   menu access
```

If the mechanic needs additional assistance, he can request it by moving the cursor to Help. As Screen 11 shows, Help provides additional information on how to perform the recommended action.

Screen 11

```
Help

As coolant temperature approaches 74 C [165 F], grasp
the radiator inlet hose about 12 inches down from the
thermostat housing. When the hose begins to warm, the
coolant temperature from the master gauge is the
radiator thermostat opening temperature.

Corresponding centigrade ranges are 75 to 80, below 75,
and above 80
```

In an expert system for inspection or repair, there would be many uses for a Help facility. Experienced mechanics may not need advice on how to perform the action, but in many cases inexperienced mechanics would. In addition to Help text, by use of laser disk technology, graphical information such as schematic diagrams could be presented. This could be an optional feature of an expert system.

In the above case, thermostat opening temperature was correct. Had it been below 170° or above 180°, the mechanic would have been advised to change the thermostat.

MARV then asks the mechanic to check the block pressure in the warm engine.

Screen 12

```
With the coolant temperature between 71
and 88 C [160 and 190 F], block pressure
at 2000 RPM should be 172 kPa [25 psi]
or higher.

  ok
 [low]

  help
  menu access
```

In this example, the block pressure was low, so the expert system first asks the mechanic to check that the water pump was working correctly.

Screen 13

```
Check that the water pump is working
correctly.

  ok
 [bad]

  help
  menu access
```

The mechanic found that the water pump was bad, and replaced it. However, the overheating problem still remained. Therefore, MARV continues to try to find the problem.

MARV now asks if air bubbles are visible in the sight glass on the OAC troubleshooting kit.

Screen 14

```
With the engine at 2000 RPM, as the
temperature increases from 77 to 88 C
[170 to 188 F], do you see air bubbles
in the sight glass


 not_observed
 observed

 menu access
```

Remember above when the mechanic answered "hard pull" to the question of "When does overheating occur?". Marv Lawson, the expert, said that a very likely cause of overheating under hard pull is gas (air or combustion products) in the system. Consequently, this and the following two questions are oriented towards checking out whether gas is in the system.

Many of the previous questions were asked to identify problems that are indicated in a vehicle before it reaches its normal operating temperature. If the problem occurs only under hard pull, the cause of overheating is not likely to be a simple malfunction of the cooling system, such as a stuck thermostat. However, while the mechanic waits for the vehicle to warm up, these other problems can be definitively ruled out without adding time to diagnostics. If these questions are not asked and the problem is not gas in the system, the mechanic must allow the engine cool off before he can continue diagnosis. A similar situation holds true for repair of motor vehicles. In some cases, the sequencing of diagnostic steps may be based upon how easy they are to perform, and not how likely they are to be the problem.

The next three screens try to find gas in the system.

Screen 15

```
As the water temperature reaches 80 to
85 C [180-185 F], at 2000 RPM, how would
you describe the block pressure ?

 [ok]
  dropping

  help
  menu access
```

Screen 16

```
[Help]

Remove the radiator cap and turn off the cab heaters.
If the engine has a Reserved Flow Cooling hose, plug it
at the thermostat housing.

Install the troubleshooting test kit and turn the lower
valve to 'block' position.  If you don't have the kit,
install a pressure gauge with a range from 0 to 60 psi
on the Compucheck fitting on the engine block.
Accelerate to high idle.

A sudden drop in block pressure of approximately 69 to
103 kPa [10 to 15 psi] is considered dropping in this case.
```

Screen 17

```
Further tests for gas are indicated.
Recheck the hot block pressure with a
dyno to put the engine on load.

As the water temperature reaches 80 to
85 C [180-185 F], at 2000 RPM, how would
you describe the block pressure ?

 [ok]
  dropping
  not_known

  help
  menu access
```

The first test occurs under high idle conditions, and is looking for a drop in block pressure. Screen 16 shows the Help text that goes with Screen 15. The second test occurs under loaded mode conditions, and again looks for a drop in block pressure. Since the block pressure did not drop under high idle or loaded mode conditions, the mechanic can definitively rule out gas in the system as a cause of the overheating problem.

The next two screens ask the mechanic to record the thermostat housing pressure and the block pressure with a fully warmed-up engine.

Screen 18

```
What is the thermostat housing pressure at 91 C [195 F] ?

 25

 [continue]   reenter    help    menu access
```

Screen 19

```
What is the block pressure at 91 C [195 F] ?

 25

  [continue]   reenter    help    menu access
```

This information is used in conjunction with pressure measurements at the same location with a cold engine (See Screens 8 and 9) to diagnose possible causes of flow restriction in the engine. The diagnosis appears on Screen 20.

Screen 20

```
Explain   E
Help      H
```

```
Remove the aftercooler and check for
blockage.

  ok
  bad

  menu access
```

Another feature of an expert system is the ability to explain the line of reasoning leading to the recommended action. In this case the recommendation is to remove the aftercooler and check for blockage. Screen 21 shows the explanation for the diagnosis of a blocked aftercooler. The explanation facility will be helpful in training Smog Check mechanics.

Screen 21

```
Explanation

Since the hot pressure is high
    when the cold pressure is high
    it is necessary to check for a blocked aftercooler
    in order to troubleshoot the flow control system


    continue    elaborate
```

Note that the explanation refers to subjective values for hot and cold pressure; for example, "high". So far the expert system has not asked if the hot or cold pressure is high. Instead, it has inferred this information based upon the thermostat housing pressure and the block pressure.

Repair of smog check failures will be similar. The expert system may say that the oxygen sensor voltage under rich operation is too low, but this may be inferred from oxygen sensor voltage readings, not by responses to a question asking if the voltage is low. The expert system could record the voltage, and based upon the type of vehicle, make the judgment as to whether it was low or okay.

At this point it is useful to point out another feature in MARV that would be very useful in an expert system for vehicle inspection or repair. This feature is the ability to view the responses to the questions that the expert system has asked. Screen 22 shows the responses to some of the questions asked thus far.

Screen 22

```
Data Window

ENGINE:    BCIV                        CHASSIS
 MILEAGE: ?          K                  FAN: viscous
                                        RADIATOR
PROBLEM:      overheating                TYPE:      ?
 SPECIFIC:    hard_pull                  BAFFLES: ?
 AMB. TEMP.: above_40 F

TESTS PERFORMED
 PRECHECK: yes                         TEMP. GAUGE:     ok
 BLOCK PRESSURE                        WATER PRESSURE
  WARM:         ok .                    COLD: high     (34   /33   )
  HOT:          ok                      HOT:  high     (25   /25   )
  UNDER LOAD: ok                        VERIFIED: ?
 GAS TEST
  BUBBLES:      ?                      AERATION: ?
  AT IDLE:      ?
```

You can see on Screen 22 where the expert system converted cold and hot pressure readings to the values of "high".

The ability to view the input data file has merit in an expert system for smog check inspections or repairs. It provides a record of the inspection or repair actions and allows the mechanic to review what has been performed so far. If some of the responses have changed, data can be re-entered. The expert system may be taking the mechanic down the wrong path because of an incorrect data entry early in the program.

The expert system session concludes by identifying other components that could be responsible for both high hot and cold pressure. These components are less likely than a blocked aftercooler, but nonetheless could contribute to the observed pressure readings.

Screen 23

Check the aftercooler filter screen.

ok
bad

help
menu access

Screen 24

Advice

Thermostat housing pressure indicates both the bypass thermostat and the radiator are plugged.

continue   menu access

Screen 25

Advice

Thermostat housing pressure indicates both the bypass thermostat and the radiator are plugged.

continue   menu access

Capabilities of Current Diagnostic Analyzers

Many different diagnostic analyzers can be found in the marketplace. Analyzers range from small hand-held devices to bench type analyzers. The functions and capabilities of the different analyzers vary as much as their size. The analyzers described in this section are currently used by many Smog Check stations throughout the state. By considering the capabilities of these analyzers in conjunction with the potential for expert systems software, the feasibility of Test Analyzer System enhancements is put in better perspective.

The operation of all of the analyzers studied is controlled by a microprocessor. In general, these analyzers can measure the quantity of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC) in the exhaust, as well as pinpoint electrical and mechanical problems with the engine/emission control system.

The analyzers studied have the capability to be used as a TAS, in addition to performing diagnostic functions. However, TASs do not require all of the capabilities which are found on diagnostic analyzers. The four diagnostic analyzers reviewed during the course of the study were:

- Allen Smart Scope,
- Bear 40-900 Diagnostic Computer,
- Hamilton VTS850, and
- Sun Interrogator 2

Diagnostic Analyzer Test Equipment - In order for an analyzer to perform adequately, certain test equipment is required. In general, the test instrumentation found on the different diagnostic analyzers is the same. The differences between diagnostic analyzers tend to be the instrumentation range and the operation of the automatic test feature. All of the analyzers studied have an automatic test feature which is used to verify the operation of the basic engine systems, i.e. starting system, charging system, base engine, ignition system, and fuel system. Although all analyzers test the same systems in the automatic mode, each analyzer manufacturer uses a different test procedure and analysis method.

The test equipment found on the four analyzers can be segregated into three categories: exhaust gas analyzers, electrical test equipment, and ignition system test equipment. Some diagnostic analyzers also have vacuum gauges, but these instruments are not found on most diagnostic analyzers.

Exhaust gas analyzers in use today can typically measure four gases: HC, CO, CO_2, and O_2. Exhaust gas analyzers are used to assist in diagnosing base engine failures, ignition system failures, and fuel system failures.

Electrical test equipment is used to measure current, voltage, and resistance. During engine cranking current draws of up to 1000 amperes can occur. During the firing of the spark plug, voltages in the secondary circuit of the ignition system can reach 50,000 volts. The equipment also requires the capability of measuring resistance up to 250,000 ohms. Electrical test equipment is used to diagnose base engine failures, ignition system failures, electronic sensor and actuator failures, and wiring problems.

Ignition system test equipment includes an oscilloscope for measuring and displaying voltage variations, a timing mechanism for measuring spark advance, and a dwell meter for measuring the charging time of the primary coil. Ignition system test equipment is used to measure engine speed when performing tests which require the engine to operate at a specified speed, and to diagnose ignition system failures and fuel system malfunctions.

Vacuum gauges are used to measure the intake manifold vacuum and the vacuum reaching vacuum operated components. By observing the intake manifold vacuum under idle and high speed operation, problems with the base engine can be diagnosed. The proper operation of vacuum operated components can also be verified by using a vacuum gauge in conjunction with a vacuum source.

Ignition System Testing - The oscilloscope is the primary tool used to analyze the ignition system. Other instruments which are used include the dwell meter and the timing light. The dwell reading needs to meet the manufacturer's specification in order for the primary coil to charge properly. The base ignition timing is verified with the timing light, or the magnetic pick-up.

The oscilloscope is used to display voltage variations. Typically the scope is timed to show the voltage variation during one engine cycle. The events displayed include the charging of the primary coil, the discharge of the coil, the initiation and propagation of the spark, and the dissipation of energy in the coil and condenser. By observing all of these events and comparing the voltage versus time display with the expected voltage trace from the given system, problems with the ignition system can be diagnosed.

Base Engine Testing - Two generic tests, the power balance test and the cranking compression test, are performed by most diagnostic analyzers to evaluate the engine's operation. These tests are used to identify cylinders which are low on compression or are producing reduced amounts of power. Base engine problems primarily cause increases in HC and CO emissions depending on the type of failure.

The cranking compression test is performed by measuring the current draw by the starter when the engine is cranking. The current draw on the starter is a measure of the power required to compress the air in a cylinder. Cylinders which do not require as much current during the compression stroke have reduced compression compared to the other cylinders. In this manner, the relative compression of each cylinder is measured and the analyzer informs the technician of significant variations between cylinders. (Cylinders which cannot adequately compress the air/fuel mixture produce reduced power and can emit significant quantities of hydrocarbons.) Base engine problems which can cause reduced compression include cylinder head gasket leaks, burned or damaged piston rings, and burned or damaged intake or exhaust valves.

The power balance test is performed by disabling the ignition system on one cylinder while the engine is idling. The analyzer measures the reduction in engine speed when the cylinder is disabled. All of the cylinders are disabled one by one and the engine speed fluctuations are compared. If a cylinder is not producing power, no variation in engine speed will occur when the ignition system on that cylinder is disabled. In this manner, dead and reduced power cylinders are identified. A number of problems could be causing the cylinder to produce reduced amounts of power, i.e. lack of compression, ignition system malfunction, or a fuel system malfunction. Locating the cylinder which is not adequately producing power is the initial step in determining the cause of the failure. Additional diagnostic procedures can be performed to pinpoint the cause of the power reduction.

By observing the intake manifold vacuum during different engine operating conditions, problems with the base engine can be identified. The absolute vacuum value and the vacuum fluctuation are both important indicators of the engine's condition. Acceptable vacuum readings depend on the number of miles on the engine and the engine type. Problems with intake and exhaust valves, ignition and valve timing, intake manifold leaks, cylinder head gasket leaks, restricted exhaust system, and many more can be identified by using the vacuum gauge.

Charging System Testing - Diagnostic analyzers measure the battery voltage and the output from the generator or alternator. Some analyzers have the capability of inducing a load on the charging system to evaluate the system's operation during heavy load operation. The diagnostic analyzer uses ammeters and voltmeters to evaluate the operation of the charging system.

Fuel System Testing - The type of testing used to evaluate the operation of the fuel system depends on the fuel system type. The typical equipment used to test the fuel system is the exhaust gas analyzer and the oscilloscope. The exhaust gas analyzer is used to measure the HC and CO exhaust concentration during the test. The oscilloscope is used to verify proper operation of the fuel control computer.

Carburetors are tested by measuring the HC and CO concentration of the exhaust during different operating conditions. The idle mixture is set by measuring the HC and CO concentration during idle. Power valve and accelerator pump operation is evaluated by measuring the HC and CO concentration during a rapid throttle opening.

Throttle-body injectors are controlled by the engine control computer. Proper operation of the injection system can be verified by measuring the fuel system pressure at the regulator, observing the output signal from the computer to the injector on an oscilloscope, and by measuring the exhaust HC and CO. Additional test equipment is required to measure the fuel system pressure. If all of the measurements are within the specifications, then the system is functioning properly.

Port fuel injectors can be analyzed by disabling the injector and measuring the hydrocarbon concentration of the exhaust. A leaking fuel injector will cause the hydrocarbon emissions to increase when it is electrically disabled. The output signal from the computer to the fuel injector can also be observed on the oscilloscope. If significant variations in the pattern or length of the injector pulse are observed, further analysis may be required.

In addition to these components, fuel systems typically include some type of pump and pressure regulating mechanism. The electronic test equipment can be used to determine whether electric fuel pumps are receiving any signals, and to test for wiring continuity from the control system to the fuel pump.

Computer and Engine Sensor/Actuator Testing - Late model vehicles are predominately computer controlled and fuel injected. In order to diagnose a problem with a computer controlled vehicle, the inputs to and outputs from the computer need to be verified. In addition, the continuity and integrity of the electrical connectors and wires needs to be verified. Some diagnostic analyzers have the capability to interface and communicate with certain engine control computers. Not all engine control computers currently have this capability. By observing the value of the input and output parameters, problems with the control system and engine can be diagnosed. This feature will become more important as the vehicle fleet turns over and the majority of vehicles on the road become computer controlled.

Special test equipment is required to communicate with engine control computers. The equipment has to be able to read the output from the computer and relay it to the technician in a manner that he can understand. Problems with engine sensors and actuators can be pinpointed using this equipment.

Some engine control computers also have the ability to perform self-diagnostic tests or to display trouble codes. Self-diagnostic tests are used to determine if the actuators and sensors are not operating properly. Some diagnostic analyzers have the capability to initiate and record the information from computer self-diagnostic tests. By recording and analyzing this information diagnostic analyzers can locate failed sensors and actuators.

Some diagnostic analyzers can read trouble codes and relay diagnostic procedures to the technician to locate the failed component causing the trouble code. These analyzers have stored in their memory the diagnostic trouble-trees which the manufacturer has developed to determine the cause of the trouble code. By combining the diagnostic information with the ability to read the trouble code, the diagnostic procedure can be performed more efficiently.

If the engine control computer does not have any of the functions described above, diagnostic analyzers can still be used to evaluate the cause of engine/emission control system problems. One of the most important engine sensors used with computer controlled fuel injection systems is the oxygen sensor. For closed-loop vehicles to operate properly, this sensor must be operational and performing according to its specification. Diagnostic analyzers can be used to measure and display the sensor's voltage output on the oscilloscope. The sensor's response to air/fuel variations can be measured in this manner.

Automatic Test Procedures - The automatic test procedure is the most useful feature of the diagnostic analyzer. During the automatic test procedure the starting system, ignition system, base engine, charging system, and fuel system are tested. Any abnormalities observed during this test are noted by the technician and discussed with the vehicle owner. This analysis, in conjunction with any symptoms noted by the driver, is the primary diagnostic tool used to pinpoint vehicle problems.

The technician informs the Allen Smart Scope about the vehicle type and any symptoms it is experiencing prior to beginning the test. During the test, the analyzer prompts the technician to perform different test sequences. Once the test is completed, a printout of the test results is made. Based on the test results and vehicle symptoms, the analyzer pinpoints the components that most likely require further diagnosis or repair. The Allen analyzer evaluates the charging system, starting system, ignition system, base engine, and fuel system.

The Bear 40-900 is similar to the Allen Smart Scope in the operation of its automatic test procedure. Like the Allen analyzer, the Bear analyzer tests the charging system, starting system, ignition system, base engine, and fuel system. At the conclusion of the test procedure, the Bear analyzer specifies which components are in need of replacement, repair, or additional diagnosis. The Bear analyzer has internal computer diagnostics so the operator does not have to look up the repair and diagnostic procedures.

The Hamilton VTS850 is similar to the other analyzers in the operation of its automatic test procedure. The Hamilton analyzer also tests the same engine systems. The Hamilton analyzer does not have diagnostics pre-programmed into its microprocessor.

The Sun Interrogator 2 tests the same engine systems as the other diagnostic analyzers during its automatic test procedure. The Interrogator 2 uses 3.5 inch floppy disks to input specific diagnostic information into the analyzer. The diagnostic information combined with the automatic test feature allows the technician to diagnose and repair vehicle problems without having to reference the manufacturers service manual.

The automatic test feature employed by all of the analyzers will pinpoint problems with the charging system, ignition system, fuel system, starting system, and base engine. The goal of the automatic test procedure is to perform a "general" vehicle diagnosis which can be combined with vehicle symptoms to pinpoint specific problems. These automatic test procedures do not evaluate the operation of engine control computers, sensors, or actuators. Additional diagnostic tests need to be performed to evaluate the operation of these vehicle components.

Advanced Test Procedures - Because of the proliferation of engine control computers, some diagnostic analyzers include test equipment which can be used to evaluate the operation of these systems. Allen has developed a product similar to a flight recorder which can record computer information from General Motors vehicles. The instrument is plugged into the assembly line data link located beneath the dash on most GM vehicles. The vehicle is then driven under the same conditions which have produced the customer complaint. During the drive, a tape player is recording the serial data stream from the computer. Information in the serial data stream includes the engine sensor values, the result of calculations performed by the computer, and output values from the computer to various actuators. After the test drive, the technician returns to the shop and connects the tape player to the Smart Scope. The technician observes the operation of the computer control system during the test drive. In this manner, intermittent problems that cannot be observed at idle can be recorded on the tape player. In order to properly diagnose intermittent problems, the technician needs to completely understand the variables being displayed and their relationship to the operation of the vehicle.

The Bear 40-900 analyzer has a similar capability. It can receive information from the GM and Ford control computers and display them on the cathode ray tube. The Sun Interrogator 2 also has similar test link capabilities using their bi-directional test link. The Hamilton VTS850 does not have these capabilities.

In conclusion, the current automatic test mode of most diagnostic analyzers can diagnose the failures which cause high emissions from many of the vehicles in the fleet today. However, the capabilities of these analyzers are best-suited to the identification of defects such as vacuum leaks and ignition misfires which are not especially difficult for mechanics to diagnose without special equipment. Except to the extent that they interpret codes from onboard diagnostic systems, the analyzers evaluated are not particularly well-suited to the identification of defects with oxygen sensors, catalysts, and EGR.

Service Industry Reaction to Advanced Diagnostic Equipment

Radian surveyed Smog Check stations in the Sacramento area that had purchased state-of-the-art diagnostic analyzers. These analyzers do not incorporate expert systems but they do diagnose emission control system problems. The purpose of this survey was to assess how an expert system might be received by the service industry and to determine problems in developing expert systems for vehicle diagnosis. Although the sample was not large enough to be considered statistically significant, it did provide a sense of how a variety of mechanics have responded to equipment that incorporates some of the features that would be possible in an expert system designed specifically for the Smog Check program. The survey identified possible problems in the reception of expert systems and ways to mitigate these problems.

During the survey, smog check station employees were asked six questions:

1. What is the approximate percentage of engine and emission control system repairs for which the diagnostic analyzer is used?

2. Do you use the diagnostic analyzer to diagnose problems with computer controlled vehicles?

3. Is the diagnostic information presented by the analyzer accurate?

4. Does using the analyzer encourage short cutting diagnostic procedures?

5. Is the equipment worth its cost?

6. What modifications would you make to improve the equipment?

A total of 17 smog check stations were contacted in the Sacramento area, of which 11 had advanced diagnostic analyzers. The specific types of analyzers that the 11 stations were using and the detailed response to the questions are described in the Appendix.

The results of the survey are shown in Table 11. A majority of the current users appear to be satisfied with the accuracy of the analyzer and its ability to diagnose engine and emission control systems problems, and yet less than half of the users felt that the equipment was worth its cost. Further investigation of equipment costs revealed dissatisfaction with maintenance costs in addition to the high initial price. If an expert system could be incorporated in the BAR90 analyzers without significantly increasing the overall price, and if BAR were to provide software updates, it is likely that cost would not be a concern with analyzer users.

Table 11

Diagnostic Analyzer Survey Results

Number of Users Surveyed	11
Approximate Percentage of Repair Actions for which the Analyzer is Used	70% (range = 15-100%)
Is Analyzer Used to Diagnose Computer-Controlled Vehicles?	Yes = 73% No = 27%
Is the Analyzer Information Accurate?	Yes = 82% No = 18%
Does Using the Analyzer Encourage Short-Cutting Diagnostic Procedures?	Yes = 18% No = 82%
Is the Analyzer Worth the Cost?	Yes = 36% No = 45% Don't Know = 18%
What Modifications Would You Make to the Analyzer?	None = 27% Improved Accuracy = 9% Have Analyzer Pinpoint Problem Better = 9% Eliminate Diagnostics = 27% Improved Reliability, Test Sequence = 27%

The results indicating that these analyzers do not encourage short-cutting of diagnostic procedures is consistent with the feelings that the analyzer generally is accurate. Because an expert system could improve the accuracy of diagnostics, users may have even more confidence in analyzers using expert systems.

Although users generally felt the analyzers were accurate, problem areas were identified. Some users said the information provided by the analyzer was too general, and that a good technician with the proper tools and information could determine the cause of the problem quicker than the diagnostic analyzer. This highlights a major concern about building an expert system for vehicle diagnosis. An expert mechanic often bypasses many diagnostic procedures and goes directly to the cause of excess emissions. An expert system for vehicle repair also must be able to do this if it is to be accepted in this field. Again, the obvious way of mitigating potential problems with expert systems is to limit their scope. For example, the expert system could assist in the inspection and diagnosis of key emission-related components such as the oxygen sensor and the catalytic converter and leave the task of diagnosing other components up to the mechanic.

In the long term, a more complex expert system is feasible, but in the short term the above approach would be most cost effective, especially in light of the causes of excess emissions from computer-controlled vehicles.

In summary, a limited survey of users of advanced diagnostic analyzers indicates that expert systems could be accepted by the service industry if they do not significantly increase the cost of the equipment and they provide accurate diagnosis quickly.

5. SMOG CHECK EXPERT SYSTEM CONCEPT

This section addresses the manner in which expert systems might be successfully incorporated into the Smog Check program. Three principal system concepts were considered: 1) a centralized, computerized system under which Smog Check stations are connected to a central computer over telephone lines; 2) a decentralized system under which each Smog Check station uses its own, stand-alone computer system; and 3) a telephone service approach under which expert counsel is available to Smog Check mechanics who call for assistance. Data acquisition options considered include ARB/BAR diagnosis of vehicles sampled from customer service and vehicle manufacturer testing programs.

Hypothetical Expert System for the Smog Check Program

In the previous section, a number of examples were provided to indicate how the expert system for cooling system diagnosis would be modified to address Smog Check related problems. Figure 3 shows the structure of a hypothetical expert system to inspect vehicles and diagnose Smog Check failures. The expert system is structured as a hierarchy of computer subroutines. The highest level subroutine is the user interface. It takes information on the task being performed (e.g., inspection or repair) and symptoms. It then provides inspection steps when the expert system is used as an expert inspector, and diagnostic and repair steps when it is used as an expert diagnostician.

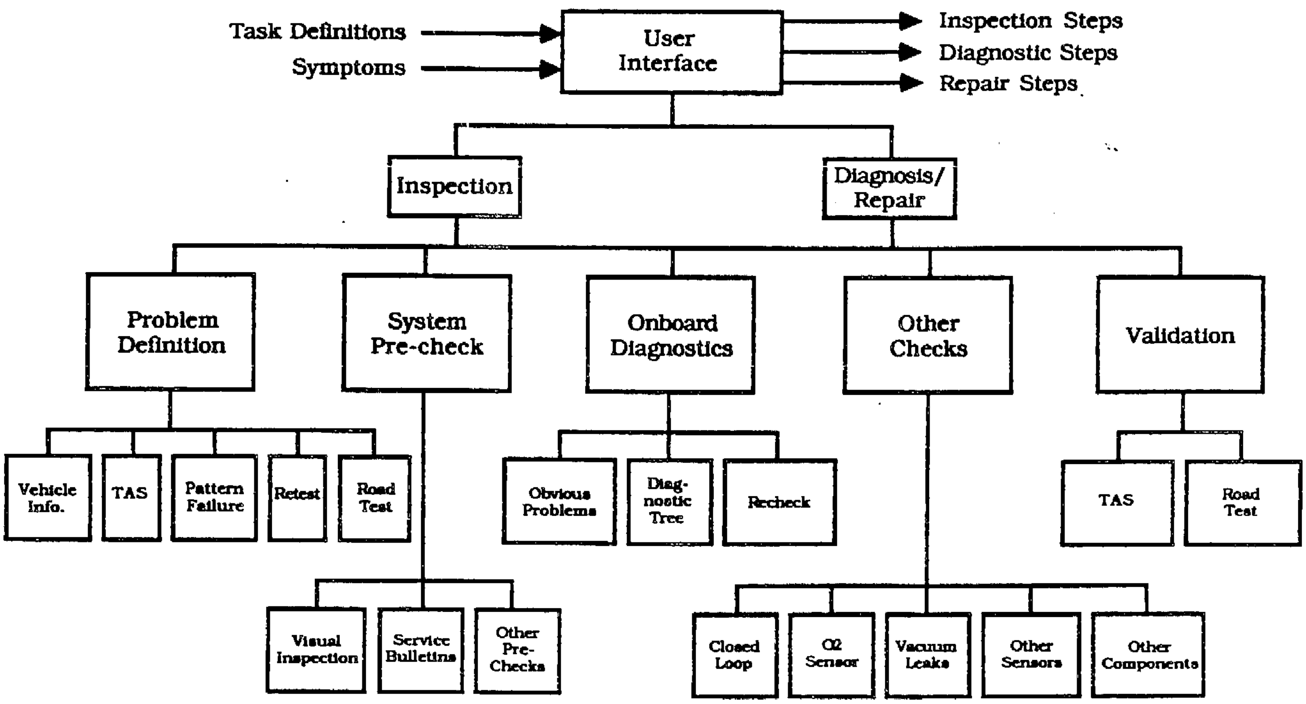
The user interface obtains information from two major modules. One provides advice for the inspection process; the other provides advice for diagnosis and repair. Both modules obtain input from several submodules. Five are shown on the hypothetical structure on Figure 3. These modules are:

1. Problem definition;
2. System precheck;
3. Onboard diagnostics;
4. Other checks; and
5. Validation.

The problem definition module is used to better define the state of the vehicle. Information on idle and 2500 rpm emission levels, illumination of onboard warning lights, and information about the vehicle is input into this module. By tying the expert system

Figure 3

Hypothetical Structure of an Expert System
for I/M Repair



directly into the TAS, much of this information will be available automatically. Otherwise, information must be manually input.

The problem definition module contains a submodule that identifies "type I" pattern failures* based upon vehicle identification and stored information regarding recall campaigns and commonly occurring defects. Another submodule could identify "type II" pattern failure*

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* EPA has defined "Type I" Pattern Failure vehicles to mean vehicle models which experience high I/M failure rates due to one or more commonly occurring defects. "Type II" Pattern Failure vehicles are models which experience a high failure rate even when no defects are present.

vehicles that should be retested after proper vehicle conditioning. The problem definition module would be helpful during the inspection process by improving the precision of the inspection, and during diagnosis by providing specific information describing the problem for use elsewhere in the expert system. (A major advantage of an expert system is that it remembers what data have been input into the system. Consequently, when these data are needed later on, such as information on vehicle make or the results of the emission test, they are available without further queries to the mechanic.)

As part of the problem definition, the results of a road test to identify any starting driveability or acceleration problems could be performed. These results could be input into the expert system to better define the problem.

The next module of the hypothetical expert system would perform prechecks of the system. In the case of inspections, prechecks could consist of a visual inspection for missing emission control components, disconnected vacuum lines, or other obvious problems. The precheck module also could identify obvious problems in the vehicle early on in the diagnostic process. The type of information requested by the system precheck module could vary depending on the equipment available to the garage. For example, certain types of equipment can easily identify ignition misfire, valve leakage, or other obvious problems. If the garage does not have sophisticated test equipment, the precheck module may be limited to the inspection results or a computerized review of service bulletin information applicable to the specific engine used in the vehicle.

The prechecks requested by the system will vary, depending on the problem definition. For example, if the vehicle failed only for CO, prechecks of the ignition system may not be advised.

The next module applies to vehicles with onboard diagnostic systems. This module recommends diagnostic steps to interrogate the diagnostic systems to obtain trouble codes indicating the nature of the problem. An important submodule to the main module could first attempt to find obvious causes based upon the trouble codes found. For example, some of the GM service bulletins list obvious problems for different trouble codes based upon driveability or fuel economy complaints.

If an obvious cause is not found or cannot be determined from available data, additional submodules could walk the mechanic through a step-by-step diagnostic procedure, or diagnostic tree, as it is sometimes called. Many of the currently available engine diagnostic equipment contain these diagnostic trees. Including them in the expert system will provide greater depth in the inspection and repair process.

A direct link-up to the vehicle computer would greatly expedite the execution of the onboard diagnostic module. This link-up could provide trouble codes along with much of the data needed to go through step-by-step diagnostic trees developed for different systems. The diagnostic trees are tedious to follow without a direct link-up between the expert system and the onboard computer.

Because some problems are intermittent, the expert system may at times recommend rechecking a certain parameter or re-executing a test procedure. The expert system would know if the computer is tied directly into the onboard computer and would be able to perform many of the checks transparently to the user; i.e., the user would not realize that they are being performed.

The "other checks" module also could be used during both inspections and repairs. If a check for closed-loop operation or oxygen sensor performance is included as part of the Smog Check as is being proposed, this module would provide procedures to do these checks on different types of vehicles. Other checks that could be performed would be functional checks for vacuum leaks, such as recommending to spray propane on hoses and monitor oxygen sensor voltage, checks of other sensors, or possibly functional checks of the catalytic converter.

The final module recommends procedures to validate that repairs have corrected problems in the vehicles. This module will only apply to diagnostic and repair functions, not the inspection functions.

Modeling Expert Mechanics - The reasoning process of a skilled mechanic is complex, so expert systems for vehicle diagnosis are necessarily going to be complex computer programs. Expert mechanics have the following characteristics that the expert system must capture:

- Extensive knowledge about vehicle repairs
- Capability to rapidly eliminate blind alleys
- Ability to change direction when new facts enter the picture, i.e., non-monotonic reasoning
- Ability to identify potential problem areas in complex systems
- Ability to work with incomplete or noisy data and yet arrive at satisfactory results
- Ability to address problems that often defy neat, tractable solutions

As the above characteristics indicate, attempts to build computer programs simulating the behavior of a skilled mechanic are going to be difficult because expert reasoning is complex. Furthermore, a great deal of knowledge must be assembled to build an expert system that approaches the performance of an expert mechanic.

One way of mitigating the problems associated with building an expert system for smog check inspections and repairs is to limit the scope of the expert system. As indicated in Section 3, malfunctions of the oxygen sensor have been identified as the cause of the majority of the excess CO emissions and over half of the excess HC emissions. In addition, these malfunctions contribute to excess NOx emissions. The catalytic converter is another significant cause of excess HC and NOx emissions, and problems in the EGR system on vehicles so equipped contribute to excess NOx emissions. To minimize the complexity and cost of the system, the focus of expert system development could be on the software primarily intended to assist mechanics in inspecting the oxygen sensor, the catalytic converter and EGR system along with other inspection items currently included in the BAR84 test analyzer system.

Implementation Options

There are three fundamentally different approaches that have been used in other applications to implement "expert systems": 1) a "centralized" computer-based system that could be accessed via modem using a "dumb" terminal; 2) a "decentralized" system using stand-alone computers; and 3) a telephone-based system relying on expert diagnosticians. Various combinations of these approaches could also be considered.

The feasibility of the decentralized concept would depend on whether the expert system could be implemented using relatively low cost computer hardware. Although a precise estimation of the memory and storage requirements of an expert system for the Smog Check program was beyond the scope of this study, experience Radian has had with other expert systems for diagnostic applications can be used for approximation. Radian has developed a small expert system to diagnose the electronic control system used for the General Motors carbureted engine lines built between 1981 and 1984. This system covers about one-third of the problems that could occur in the electronic control system. The executable version of the Expert System requires approximately 100 kilobytes of memory.

Personal computers based on the "IBM Personal Computer" standard can utilize at least 640 kilobytes of relatively inexpensive random access memory (RAM). (Most IBM-compatible PC's can readily be equipped with an additional 2 megabytes of supplemental RAM conforming to the "EMS" or "EEMS" standard.) For a specific vehicle model, even 640 kilobytes would appear to be sufficient to execute an expert system from main memory, based on Radian's experience with GM systems. Variations in the program for all of the models subject to the Smog Check program could be stored on disk and loaded into memory when needed.

A few bytes of data would be used to determine which elements of the expert systems software should be utilized. (Vehicles equipped with multipoint fuel injection and oxygen sensors would utilize different programs than open-loop vehicles equipped with carburetors.) By using software to generate messages from stored data, information such as "Check all 1986 Chevrolet passenger car models with 350 CID engines for underhood label indicating completion of Recall Campaign C-86-004" or "This vehicle frequently experiences throttle position sensor failures" could be coded with only a few bytes of information stored in a specific field of the data record for each model. For example, only 6 bytes of information would be needed to generate the message to check for compliance with a six-digit recall campaign number.

One thousand bytes of information could provide a substantial amount of information regarding each specific model subject to the Smog Check program. This could easily cover the emission control system configuration, the interpretation of diagnostic codes from the onboard computer, and extensive information regarding commonly occurring defects that may have been reported for a particular make or model. Where ARB testing has indicated it would be appropriate, engine family specific emission standards could also be used. The total number of passenger car and light truck engine families certified in 49-states and California each year is typically less than 400, many of which are very low volume families. Assuming engine family specific information was desired for 300 engine families for each model year and twenty model years, 1 kilobyte of information for each family would require about 6 megabytes of data storage. The inexpensive, 20-30 megabyte mass storage available for personal computers would appear to be more than adequate.

Centralized Expert Systems - With a centralized expert system, the user, i.e., the Smog Check mechanic, would access the system via a terminal at the repair shop that is tied in by phone lines to a centralized computer that contains the expert system. The knowledge base in the centralized computer, i.e., the data base of expert decision-making that is the heart of the expert system, would be continually updated and expanded as new vehicle types are introduced or new information is discovered about the causes of excess emissions and, accordingly, I/M failure. The centralized computer could maintain a log of the types of problems that it is requested to solve, as well as a log of the users.

Potential advantages associated with the use of a centralized Expert System for repair of smog check failures include:

- The system would be more easily updated because the data base is centralized;
- The system would have virtually no limitations on memory;
- The overall system cost could potentially be lower because there is no need for computers at each inspection station; i.e., terminals are cheaper than computers; and
- Data on problems being encountered by Smog Check stations are available on a real time basis.

Potential disadvantages associated with a centralized Expert System include:

- Unless the system is designed with substantial excess capacity (and cost) availability of the system and system response time could be a problem during peak periods of inspection activity;

- When the central system is down for repair, every garage participating in the Smog Check program is affected; and

- Direct link-up with a vehicle onboard computer or TAS may be more difficult than with a decentralized option.

Decentralized Expert Systems - With a decentralized expert system, the system would be resident upon a personal computer located at each smog check facility. The knowledge base could be stored either on floppy disks or on a hard disk or other mass storage device in the computer. The mass storage device would obviously be the most desirable option since the mechanic would not have to handle floppy disks. When the expert system is interrogated, applicable portions of the problem would be taken from the storage device and placed into RAM (Random Access Memory). In this way, the expert system could solve a wide variety of problems despite the memory limitations of the personal computer.

There are two potential advantages with a decentralized Expert System:

- System availability and response time are expected to be much less of a problem; and

- Interfacing directly with the TAS or onboard computer is likely to be easier.

A secondary but nonetheless important advantage is that a decentralized Expert System does not have to be logged off between repair steps, i.e., the mechanic can keep the system on deck awaiting the response to the recommended repair action.

When compared to a centralized Expert System, a decentralized system has several disadvantages:

- More difficult to update. Expert systems constantly need updating, which will be more of a problem with the decentralized approach. One way of minimizing the problem with updating would be for the expert system, i.e., the personal computer, to access a centralized knowledge base via phone lines and receive an updated knowledge base to replace the existing knowledge base. Updating via floppy disks is another option.

- The system is potentially more expensive. The cost of personal computers is greater than the dumb terminals used to access a centralized computer; and

- Real time tracking of field problems is not possible.

Telephone-Based Systems - The third basic method by which smog check mechanics could receive expert guidance is through the use of a telephone advisory service. Mechanics would be given a toll free number to call for advice on difficult to diagnose problems. Experts would be available to the mechanics during certain hours of the day. These experts would be automotive technicians who have access to an expert system and are proficient in the use and operation of the system. An organization very similar to this description is currently operating in Huntington Beach, California. Automotive Data Systems, or ADS, is a hotline for technicians having difficulty diagnosing problems on vehicles which are in their shop.

The primary focus of ADS is aiding in the diagnosis and repair of engine performance and driveability problems. Their data base currently includes information on automotive and light-truck Diesel and gasoline powered vehicles. The information spans model years from 1964 through the current model year for both domestic and imported vehicles.

Different sources of information are used by ADS to update and expand their data base. Product information bulletins, service bulletins, parts manufacturers, engineers, and dealership mechanics are all information sources that ADS uses to update and expand their data base. Published information is the most significant source used to expand their data base. Additional information comes from mechanics in the field. Through their contact with mechanics, ADS employees have developed a working relationship with many of their customers. Skilled mechanics in the field provide feedback on diagnostic procedures, as well as gathering data for ADS. Discussions with working mechanics pinpoint new problems, as well as useful diagnostic procedures these individuals have developed for the problems they have encountered.

Finally, ADS's own staff of skilled technicians is constantly analyzing and developing new diagnostic procedures and tests. ADS will rent vehicles which they do not have experience with, or vehicles which have a number of field complaints. ADS uses these vehicles to validate and develop new diagnostic procedures. Using the rented vehicles, the staff learns how the new vehicles and their emission control systems function. Also, the staff then has an understanding of the complexities facing mechanics as they attempt to diagnose problems with late model vehicles.

All of the information which ADS obtains is included in their computer data base. ADS has developed the data base to meet their needs, the data base is one-of-a-kind and has been developed specifically for them. In many instances, the advisor will not use the data base to assist the caller. This can occur because all of the advisors employed by ADS are skilled technicians in their own right. These individuals are interested in automobiles and have continued to stay informed of changes and advances in automotive service. If the advisor is not familiar with the problem, he will then access the data base. Upon access, the advisor can determine if ADS has seen this problem before. If he cannot find a record of the problem, the advisor will turn to a service manual for guidance. In this instance, ADS and the technician will jointly attempt to solve the problem. This occurrence is rare, but it does happen. The data base is also expanded by this means and ADS determines which vehicles are having difficulty in the field. Even though ADS does not have the answer for the mechanic, he now has an experienced, skilled technician assisting him with the diagnosis. In most cases, the problem has been catalogued in the data base and the advisor can give the caller the specific advice he needs to diagnose the problem.

ADS provides step-by-step guidance through diagnostic procedures which will assist mechanics in pinpointing the cause of vehicle driveability and performance problems. ADS employees are skilled technicians who are familiar with the problems and solutions to difficult problems. They are capable of understanding the needs of the callers as well as being able to communicate with the caller. If the problem is one which ADS is not familiar with, the experience and qualifications of the advisor will result in a thorough diagnostic process leading to the cause of the problem and updating of the ADS data base.

There are many advantages and some significant disadvantages to accessing an expert system through a third party by talking over the telephone. The primary advantages are:

- Easier to implement. With this option, users only have to have a telephone. The expert system only needs to be installed in one location, i.e., where the centralized expert system operators are located;

- Better definition of the problem through a human interface. A human being can help better define the problem, and may help the mechanic fix the vehicle in a shorter period of time;

- Easier to update. Like the centralized expert system option, this option is easier to update than the decentralized option. In addition, the expert system operator could provide much assistance to the expert system developer in improving the system; and

- Easier to collect data on problems in the field. Like the centralized option, the use of a third-party expert system operator allows feedback on the kinds of problems mechanics are encountering that are difficult to repair. In addition, the human interface allows better definition of these problems than strictly a data record maintained by a centralized computer.

The disadvantages of using third-party expert system operators at a centralized location are significant and are listed below:

- It cannot tie into an on-board computer. It would be very difficult to tie into an on-board computer with this option. Although it is possible that the third party could work in conjunction with a centralized expert system that has access to the vehicle computer information, in actuality the primary method to transmit data is likely to be talking on the phone;

- Advice may be cumbersome. Complex problems will require several phone calls. This would decrease the effectiveness of this option and discourage mechanics from calling in for advice;

- Limits on the scope of advice. The other options discussed so far can provide specific text instructions on how to perform the diagnostic or repair action that is being advised. With this option, however, it will be difficult to provide these types of detailed instructions over the phone; and

- Availability and cost. The maximum number of mechanics that could use the expert system with this option might be limited. More expert system operators could be trained, but this would drive up the operating costs. This could be a significant drawback if a requirement is made that all Smog Check repairs must involve the expert system.

Comparison of the Options - Under the current Smog Check program, there are an average of 40,000 tests conducted each business day (Monday-Saturday). If these tests occurred in completely uniform manner, eight hours per day, and if they lasted 20 minutes each, there would be 1,667 users logged in to a centralized system or telephone advice based system at all times. As a practical matter, the system would have to be designed to accommodate several thousand users at one time in order to avoid availability problems. The personnel implication for a telephone advice-based system is obviously a problem. Assuming the fully-burdened cost of having humans available to provide expert advice is $30 per hour, the per test cost could be in the neighborhood of $10.

The hardware costs of serving several thousand users simultaneously with a centralized system is obviously substantial. Substantial costs are also associated with the telephone line charges associated with the use of the system. Assuming line charges can be held to $6 per hour through the use of volume discounts on a Telenet-type service, the average line charges per test would be $2. Each station would also require a dumb terminal and modem, estimated to cost about $500.

For decentralized systems the hardware cost for even a stand-alone system is estimated at only about $1,000 per system (8088-2 CPU, 640KB RAM, monochrome CRT w/video display adapter, keyboard, serial communications port, floppy disk drive, 20-30MB fixed disk).

On a per test basis, the cost of these two competing options is estimated as follows:

	Decentralized Option	Centralized Option
annualized cost of Smog Check Station equipment*	$264	$132
annualized cost of central computer	n.a.	ignored
periodic update cost/test	ignored	trivial
capital cost per test†	0.18	0.09
phone line charges per test	0	2
Total	$0.18	$2.09

Although the cost of periodic updates of the decentralized system has been ignored in the above analysis, it is unlikely that it could approach the cost differential between the centralized approach and decentralized approach shown above. If updates were combined with quarterly inspections of Smog Check stations, the cost per test could be minimal.

Data Acquisition Options

Data sources for the maintenance of expert system software include:

- ARB and EPA in-use surveillance data,
- special testing programs involving more detailed diagnostic procedures than typically included in surveillance testing programs,
- random roadside inspection program data,
- defects reporting by vehicle manufacturers, and
- analysis of data recorded by Test Analyzer Systems.

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* estimated over 5 years at 10% cost of funds.
† estimated based on 1,500 tests per year

Since the effectiveness of expert systems is based on the amount of information available, all available data sources should be utilized. The available data will need to be analyzed on a periodic basis to determine how expert system programming should be modified.

System Development Options

There are a variety of implementation options that could be pursued for the development of expert systems software and hardware. The two extremes are:

1. BAR or ARB sponsored development of detailed hardware and software specifications, and

2. Independent hardware and software development based on BAR/ARB guidelines.

The obvious disadvantage of the State taking the responsibility for the development of detailed specifications is that of lead time and cost to the State. Analyzer vendors have more experience and will be willing to invest their own resources toward the development of a new TAS in expectation of profiting from the sale of analyzers in the future. Since previous California specification analyzers have been adopted by other states, the potential returns for vendors are enormous and there should be no problem motivating them to act.

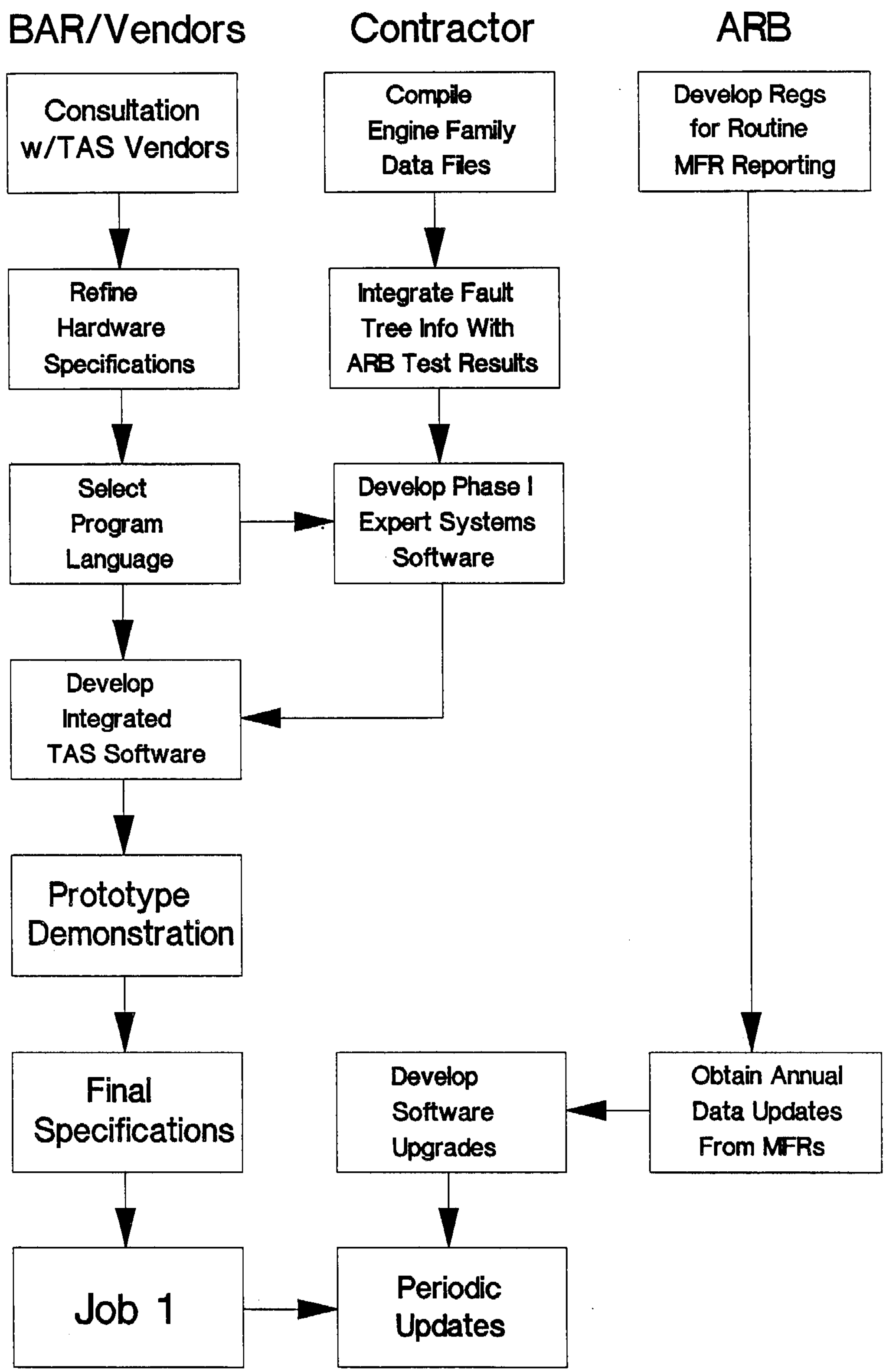
However, giving total responsibility to analyzer vendors has its disadvantages also. This is the approach that was used with the BAR'84 analyzer. As a result there are fundamental hardware and software differences between vendors and the cost of system upgrades is maximized.

The optimal approach may involve having BAR require somewhat greater hardware consistency and much greater software consistency. In particular it might be desirable for BAR to require all vendors to utilize the same expert systems software. Since the software development cost is expected to be substantial, this would significantly reduce the cost of the new analyzers. In addition, it would minimize the cost of system upgrades.

Figure 4 is a simplified flow chart of a possible implementation approach. Under this approach, one organization is given lead responsibility for expert systems software development and maintenance.

Figure 4

1990s TAS Implementation Option



6. RECOMMENDED TEST ANALYZER SYSTEM CHANGES

Based our review of commonly occurring failure modes and the potential for obtaining more effective diagnosis and repair through the use of expert system software, it appears that there could be significant benefit to providing additional computer assistance to Smog Check mechanics. Furthermore, it appears that it would be most feasible and cost effective to provide additional computer assistance through modifications to the Test Analyzer Systems used in Smog Check stations.

This section summarizes the findings and discusses how they relate to possible changes in the inspection and repair procedures programmed into Test Analyzer Systems. In addition, this section addresses other possible TAS modifications that appear desirable based on analysis of available TAS data.

Background

The Test Analyzer Systems used in the California Smog Check program (referred to as "BAR'84" analyzers) represent the most significant advance in decentralized (private garage) vehicle inspection and maintenance thus far. Prior to the use of BAR'84 analyzers, inspection results were recorded on simple paper forms and a very limited amount of data was available for analysis. Computer analysis of the inspection data was not feasible and there was no assurance that any of the information written on the form was accurately recorded. Studies conducted by ARB showed that the accuracy of recorded inspection results was very poor.* With the use of the computer-controlled BAR'84 analyzer, it became possible for a greater amount of information to be recorded and much of that information could be automatically recorded by the analyzer. Accurate information regarding tailpipe emission concentrations and engine speed was ensured.

The BAR'84 analyzer incorporates a video monitor which prompts the operator to enter information regarding the vehicle being tested. The operator communicates with the analyzer through a typewriter-style keyboard (some systems use the typewriter-style "Qwerty" layout, others have the keys arranged in a simple alphabetical order). A printer produces a copy of the test results at the completion of

* T.C. Austin and G.S. Rubenstein, "A Comparison of Private Garage and Centralized I&M Programs," SAE Paper No. 790785, August 1979.

testing. A bottle of calibration gas is connected to the analyzer to facilitate an automated calibration sequence. The analyzer is powered by 110 volt, AC current and contains battery backup to keep the system clock running in the event of a power interruption.

BAR'84 analyzers are equipped to store on cassette tape any information entered by an inspector or measured by the analyzer. Operator-entered information includes:

- vehicle description;
- license plate number;
- odometer reading;
- emission control system visual inspection results;
- emission control system functional inspection results;
- description of repair actions performed;
- description of repair actions not performed because of a repair cost ceiling; and
- the cost of repairs performed.

Data that are sensed by the analyzer and automatically recorded on cassette tape include:

- exhaust emission concentrations;
- engine speed; and
- time and date.

In addition, BAR'84 analyzers also remember the length of time that has transpired since the last instrument calibration, and they prevent inspections from being performed when the maximum time between calibrations has been exceeded. The analyzers require operator entry of a "password" to limit use of the analyzer to individuals who have met BAR licensing requirements and been issued a unique identification number and password. When a valid password is entered, the identification number of the operator is stored on the cassette tape along with other information regarding a particular test.

Visual and functional test results recorded on BAR'84 analyzers are an important element of the inspection program. Practical considerations have limited the emissions tests used in I/M programs to relatively simple, steady-state measurements of exhaust emissions from warmed-up vehicles. The correlation between these steady-state tests and actual emissions in customer service is poor. The inherently poor correlation between steady-state tests and customer service emissions has required the establishment of I/M emission standards (or "cutpoints") that have demonstrated a low error of commission rate. In other words, the emission standards must be set numerically high enough to <u>not</u> fail vehicles that would pass the full, cold start Federal Test Procedure. However, many vehicles with emissions greatly in excess of the FTP standards will pass such a test. In addition, problems with crankcase emission controls and evaporative emission control systems are not detectable through exhaust emission measurement. Furthermore, defective EGR systems cannot be detected through the measurement of emissions under idle operation where most EGR systems are switched off.

For these reasons, the effectiveness of any I/M program depends on whether visual and/or functional checks of emission control systems are included. There are twelve visual inspection categories programmed into BAR'84 analyzers. They are PCV, thermostatic air control systems, air injection, fuel evaporative controls, fillpipe lead restrictor, oxidation catalyst, 3-way catalyst, EGR, ignition spark controls, closed loop air/fuel ratio control systems, carburetor or fuel injection, and a catch-all category of "other". Mechanics are required to enter visual inspection results as either "P", "D", "M", "S", or "N". The meanings of these terms are as follows:

> "P" indicates the vehicle passed the visual inspection of a particular type of device;
>
> "D" indicates the vehicle had "disconnected" emission control devices in a particular category;
>
> "M" indicates the vehicle had "modified" emission control devices;
>
> "S" indicates the vehicle had "missing" emission control devices; and
>
> "N" indicates that the vehicle was not factory equipped with a particular type of device.

For functional inspections, there are only three categories: engine warning lights, ignition timing, and EGR. For each of these items the possible entries are "P" for pass, "F" for fail, and "N" for not applicable.

There are seven possible repair actions that may be recorded using the BAR'84 analyzer. They are "misfire", timing adjustment, air/fuel ratio adjustment, crankcase, fuel evaporative control system, a catch-all category called "exhaust control", and EGR.

The total amount of information that may be stored in each "record" on the cassette tape is limited to 256 bytes. The amount of information actually recorded depends on the type of test (initial or after-repair) and the detailed inspection requirements of the particular region in which the analyzer is being used (more information is recorded in areas where functional inspections are required). In the functional inspection areas, 183 bytes of information are recorded. Through software changes, additional information could be added in the future, up to the 256 byte limit.

Table 12 shows all of the information that is currently recorded by BAR'84 analyzers used in the California Smog Check program. In addition to a brief description of each item recorded, the table also shows the length of each field, and the type of entry that may appear in the field.

Table 12

Current California TAS
Vehicle Inspection Data Record Format

Field No.	Field Description	Field Length	Field Contents
1.	Station Number	8	alphanumeric
2.	TAS Number	5	alphanumeric
3.	Mechanic Number	9	alphanumeric
4.	Date of Test	6	MMDDYY (numeric)
5.	Test Start Time	4	HHMM (numeric)
6.	License/VIN	8	alphanumeric
7.	Vehicle Type	1	P, L, M, H, or T*
8.	GVW	5	numeric or unused*
9.	Vehicle Make	4	alpha
10.	Vehicle Model Year	2	numeric
11.	Number of Cylinders	2	numeric
12.	Vehicle Engine Size	5	numeric followed by I, L, or C
13.	Odometer Reading	4	100's of miles
14.	Test Type	1	I, B, A, or R
15.	Fuel Type	1	E, G, M, N, or P
Visual Inspection Results:			
16.	PCV Valve	1	P, D, M, S, or N
17.	Thermostatic Air Cleaner	1	P, D, M, S, or N
18.	Air Injection	1	P, D, M, S, or N
19.	Fuel Evap. Controls	1	P, D, M, S, or N
20.	Fillpipe Restrictor	1	P, D, M, S, or N
21.	Oxidation Catalyst	1	P, D, M, S, or N
22.	3-Way Catalyst	1	P, D, M, S, or N
23.	Exhaust Gas Recirculation	1	P, D, M, S, or N
24.	Ignition Spark Control	1	P, D, M, S, or N
25.	Closed Loop Metering	1	P, D, M, S, or N
26.	Carb. or Fuel Injection	1	P, D, M, S, or N
27.	Other	1	P, D, M, S, or N
28.	Not Used	1	blank
29.	Not Used	1	blank
30.	Not Used	1	blank

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Current California TAS
Vehicle Inspection Data Record Format
(continued)

Field No.	Field Description	Field Length	Field Contents
Functional Check Results:			
31.	Engine Warning Lights	1	P, F, or N
32.	Ignition Timing	1	P, F, or N
33.	Exhaust Gas Recirculation	1	P, F, or N
34.	Not Used	1	blank
35.	Not Used	1	blank
36.	Standards Category	2	numeric
37.	Previous High RPM HC	4	1 PPM units or blank
38.	Previous High RPM CO	4	.01% units or blank
39.	Previous Low RPM HC	4	1 PPM units or blank
40.	Previous Low RPM CO	4	.01% units or blank
41.	Current High RPM HC	4	1 PPM units
42.	Current High RPM CO	4	.01% units
43.	Current High RPM CO2	3	.1% units
44.	High RPM	4	numeric
45.	Current Idle RPM HC	4	1 PPM units
46.	Current Idle RPM CO	4	.01% units
47.	Current Idle RPM CO2	3	.1% units
48.	Idle RPM	4	numeric
49.	Test Results	1	P, F, or A
50.	Emission Reduction	1	R, N or blank
51.	Parts Cost	4	1 $ units or blank
52.	Labor Cost	4	1 $ units or blank
Repairs Performed:			
53.	Misfire	1	Y, N, E
54.	Timing Adjustment	1	Y, N, E
55.	A/F Ratio Adjustment	1	Y, N, E
56.	Crankcase	1	Y, N, E
57.	Fuel Evap.	1	Y, N, E
58.	Exhaust Control	1	Y, N, E
59.	EGR	1	Y, N, E
60.	Exceeds Cost Limit	4	1 $ units or blank
61.	Not Used	7	blank
62.	Certificate Number	9	alphanumeric
63.	Escape Code #4	2	numeric
64.	Escape Code #3	2	numeric
65.	Escape Code #2	2	numeric
66.	Escape Code #1	2	numeric
67.	Tampering	1	X, C, T, or blank
68.	Test End Time	4	HHMM
	Total ...	183	

The BAR'84 analyzer has contributed greatly to the fact that the current California Smog Check program is achieving significant reductions in emissions. However, roadside survey data indicate that the quality of the inspections is still inadequate.* Much greater visual and functional failure rates have been recorded for random samples of vehicles stopped by the California Highway Patrol than are reported by mechanics inspecting vehicles under the Smog Check program. In addition, the I/M Evaluation Program indicated that the quality of repairs performed at Smog Check stations is deficient. Finally, TAS data analysis performed by Sierra indicates that data entered from the keyboard by mechanics is often internally inconsistent and inaccurate.

Significance of Failure Mode and Diagnostic Procedures Analysis

Changes to the inspection categories could improve the quality of inspections in two ways. First, by prompting mechanics to make more specific inspections, it is possible that some greater care will be taken during the visual and functional inspection process. Second, by automating some of the inspections, the variability in mechanic performance would be entirely eliminated.Repair quality might also be improved by prompting mechanics to record whether more specific repair actions were taken.

The type of specific inspections that would be the most effective to add to the TAS has been determined from the analysis of the most significant failure modes and the most effective diagnostic procedures identified under the analysis performed by Radian Corporation. As discussed in Section 3, Radian determined the most significant causes of excess HC emission from late model vehicles to be 1) oxygen sensor disablements or defects, 2) reduced catalyst efficiency, and 3) defective air flow sensors. For vehicles receiving repair cost waivers, these three categories of defects accounted for about 80% of the excess HC emissions identified in late model vehicles equipped with feedback control systems and 3-way catalysts. Oxygen sensors and catalysts alone accounted for most of the excess HC emissions.

For carbon monoxide emissions, the same items were the principal source of excess emissions. Oxygen sensor defects were even more significant. Oxygen sensor and catalyst defects combined accounted for almost 80% of the excess CO emissions.

For oxides of nitrogen emissions, reduced catalyst efficiency was the principal source of excess emissions. For vehicles that use EGR, EGR defects are the second biggest problem. For vehicles that do not use EGR, oxygen sensor defects are the number two problem.

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* "Evaluation of the California Smog Check Program, Technical Appendix," Sierra Research, Inc., April 1987.

Sierra's analysis of the causes of excess emissions in older vehicles indicates that "tuneup" items are much more significant. Ignition system defects which cause misfiring are a consistent source of excess emissions in pre-1980 models. Disconnected or defective vacuum lines are another significant problem. Idle air/fuel ratio adjustments were found to be another common defect. Finally, the higher tampering rate for older vehicles and the existence of component defects result in the replacement of emissions control components being a significant means of reducing excess emissions.

Specific types of defects in older vehicles that were frequently observed during the I/M Evaluation program included:

- vacuum hoses leaking or disconnected,
- air injection plumbing leaks,
- missing air pump belts,
- defective pulse air valves,
- defective sensors (especially TVS),
- defective spark plug wires, and
- fouled spark plugs.

Because 1980 and later model vehicles do not have readily adjustable idle air/fuel ratios, improper adjustments of air/fuel ratio may not become a problem as these vehicles grow older. Other problems identified with older vehicles (ignition defects, vacuum line defects, and tampering) will probably occur with greater frequency as the 1980 and later model vehicles accumulate more mileage.

An evaluation of available diagnostic procedures to isolate the cause of excess emissions indicates that oxygen sensor and catalyst efficiency problems can be identified with relatively simple procedures. Successful procedures that have been developed under ARB-sponsored work by Energy and Environmental Analysis, Inc. (EEA) and Radian Corporation are as follows:

- <u>The Catalyst Diagnostic Check</u> involves removing a spark plug wire to generate large amounts of unburned hydrocarbons, then measuring the HC concentration at the tailpipe after passing through the catalyst. A "baseline" test is performed to avoid mis-diagnosing an engine out HC problem as a catalyst problem.

The concept behind the catalyst test can be best illustrated by considering a simplified equation for the combustion of gasoline:

$$C_8H_{18} + 12.5\ O_2 + 47\ N_2 \twoheadrightarrow 9\ H_2O + 8\ CO_2 + 47\ N_2$$

As shown in the above equation, one mole of octane (C_8H_{18}) requires 12.5 moles of oxygen in order to be completely burned to carbon dioxide and water vapor. Since air is approximately 21% oxygen and 79% nitrogen, there are 3.76 (0.79 ÷ 0.21) moles of nitrogen that are ingested by the engine for every mole of oxygen required. Hence, 47 moles of nitrogen (3.76 × 12.5) are involved in the combustion of one mole of octane. If a misfire occurs, one mole of unburned gasoline will be emitted from the cylinder along with 59.5 moles of oxygen and nitrogen. The concentration of unburned gasoline in the mixture would be 16,500 parts per million (1 ÷ 60.5). Since HC emissions are generally measured as ppm <u>hexane</u>, the adjusted concentration on a hexane basis would be 22,000 ppm (16,500 × [8 ÷ 6]). At the tailpipe, this concentration would be reduced as a result of dilution from the exhaust of cylinders which are not misfiring. In a four cylinder engine, the expected tailpipe concentration <u>assuming no catalyst</u> would be about 5,000 ppm. If the catalyst is functioning properly, it would be expected to reduce emissions by about 80%. Therefore the emissions should drop to about 1,000 ppm. If the tailpipe emissions are significantly above this level, degraded catalyst efficiency is apparent.*

Using a similar calculation method, pass/fail criteria for the catalyst test can be calculated for engines with different numbers of cylinders. Adjustments can also be made for non-stoichiometric conditions. When an engine is equipped with an air injection system, the pass/fail criteria can be adjusted to reflect the additional dilution caused by the air injection and the greater amount of thermal oxidation that may be expected from the presence of the air injection system. It should be noted that the spark plug disconnect test could expose the catalyst to high temperatures if the disconnect condition persists for an extended period. With automated testing, there is no significant risk of catalyst damage.

- <u>O2 Sensor/Closed Loop System Performance Check</u> - This procedure involves checking the full scale voltage output from the oxygen sensor under induced rich and lean conditions. After verifying the operation of the O2 sensor first, computer response is checked by the "finger test" by observing the change in O2 sensor output as measured by a voltmeter. Closed-loop control is verified by warming up the vehicle and confirming an average sensor output voltage of around 0.5 volts.

The "finger test" referred to in the oxygen sensor and closed loop system performance check involves holding onto the lead which normally

* Some investigators have concluded that the spark plug disconnection test is not effective. However, earlier work has failed to address the relationship between emissions with plug disconnection and the number of engine cylinders. In addition, earlier work has failed to account for the effect of air injection use. By accounting for air injection and number of cylinders, Sierra believes the spark plug disconnect test can be effective.

connects the oxygen sensor to the feedback control system while the battery terminals are touched by one finger on the opposite hand. When the positive terminal is touched, the feedback control system receives a positive voltage which tells the system that a rich mixture condition has been detected. If the system is functioning properly, this should drive the air/fuel mixture to the lean limit. If the oxygen sensor is functioning properly, a voltmeter connected to the oxygen sensor should respond to this lean operating condition by generating a voltage output near zero. When the negative lead of the battery is touched, the feedback control system should be driven to the full rich condition and the oxygen sensor should produce an output of approximately one volt. As this test is being performed, driving the air/fuel ratio to the rich limit should produce a slight increase in engine speed and an increase in HC and CO concentrations. Driving the system to the lean limit should have the opposite effect.

Recommended TAS Modifications

Supplemental Visual Inspection Categories - There could be benefits from the incorporation of more specific visual inspection requirements for other components. For example, vacuum line defects have been determined to be a significant problem, but there is no specific inspection requirement for vacuum line defects incorporated into the TAS currently. Based on the results of the I/M Evaluation Program and ARB studies of defects in late model vehicles, additional defects to be specifically addressed under a revised visual inspection could include the air injection pump, the air pump belt, pulse air reed valves, air injection plumbing, air injection system diverter valve, electrical connections to the oxygen sensor and other sensors and switches, and whether there are any fault codes stored in the onboard computer.

Automated Functional Inspections - Under the current Smog Check program, analyzers are programmed to prompt mechanics to perform only a simply visual inspection of the catalyst and closed loop control system. The type of diagnostic procedures discussed above are not required. Given the importance of oxygen sensor and catalyst performance, there could be significant benefits to incorporating these functional test procedures into the TAS.

Incorporation of the catalyst efficiency check into the TAS would require the addition of a spark interrupter lead. Spark interruption is a standard approach used during "cylinder balance" tests performed by diagnostic analyzers currently on the market. One spark plug wire would be disconnected and the spark interrupter lead would be inserted between the end of the wire and the plug. After taking a baseline emissions measurement, the TAS would be programmed to interrupt the spark to one cylinder for a few seconds and the change in tailpipe emission concentrations would be measured. Using the logic discussed above, a pass/fail determination would be made based on whether the apparent catalyst efficiency was in the range of 80%.

Automation of the oxygen sensor and feedback control system check could also be accomplished through the use of leads from the analyzer connected to the vehicle. These leads could be attached after the oxygen sensor is disconnected from the feedback control system. One point of connection would be to the terminal on the oxygen sensor and the other would be to the wire that was disconnected from the sensor. Simultaneous measurement of engine speed and tailpipe emission concentrations would be made with the rpm pickup and exhaust probe.

The automated test would consist of three phases. First, the voltage output of the oxygen sensor would be allowed to pass through to the feedback control system leads. During this "normal" operating mode, the sensor output should vary from near zero to near one volt, indicating that the system is functioning. During the second phase, the oxygen sensor output would be electronically disconnected from the feedback control system leads and no voltage would be applied to the feedback control system. This simulates a lean condition and the feedback control system, if functioning properly, should drive the air/fuel ratio to the rich limit. A slight increase in engine speed and approximately 1 volt output from the oxygen sensor should be recorded. On vehicles that are not equipped with air injection, tailpipe HC and CO emissions should also rise. The final phase of the test would involve having the TAS apply one volt to the feedback control system. This simulates a rich condition and the feedback control system, if functioning properly, should drive the air/fuel ratio to the lean limit. The engine speed should drop and sensor output should be near zero.

Since some 3-way catalyst systems do not operate in "closed-loop" mode at idle, the oxygen sensor/feedback system check may need to be run with the throttle linkage held open by a fixed amount. On other vehicles it may be necessary for the transmission to placed in gear. The selection of the operating mode for each specific vehicle could be selected based on information stored in the TAS for each make and model of vehicle subject to the program.

Both the catalyst efficiency check and the oxygen sensor/feedback control system check introduce the possibility that a properly functioning vehicle may be adversely affected by damage to, or improper reconnection of, the wiring that is disconnected in order to perform the test. In order to minimize this possibility, there are two possible approaches that could be followed. The first approach would involve only running the test on vehicles that have tailpipe emission concentrations above a certain level. This threshhold level could be equal to or lower than the emission standards to which the vehicle is subject. The second approach would involve adding an additional test mode during which emissions are measured after the leads have been disconnected from the vehicle and the vehicle wiring is reconnected. If emissions are significantly higher during this final testing mode, the mechanic could be prompted to check the connections.

<u>Bar Code Reader</u> - Automated transfer of information to TAS systems through the use of bar code readers is another potential upgrade related to the inspection of each vehicle. In its April, 1987 report to the Legislature on the California Smog Check program, the I/M Review Committee stressed the importance of proper engine and emission control system diagnosis to the overall effectiveness of the program. The Committee specifically recommended that machine-readable bar codes, containing emission control system characteristics, idle speed, and other information, be incorporated in underhood labels as soon as possible on all new cars and trucks. Using machine-readable bar codes would eliminate entry of inaccurate vehicle and emission control system descriptions, which leads to the selection of the wrong idle emission standards, erroneous engine adjustments and other improper repairs.

At a public hearing in Sacramento on September 10, 1987, the California Air Resources Board adopted new regulations covering vehicle labeling. These regulations require that machine-readable (bar-coded) labels containing the Vehicle Identification Number and Vehicle Emission Control information be installed on 1990 and later model year passenger cars, light-duty trucks, medium-duty trucks, and heavy-duty gasoline engines and vehicles. The ARB staff report indicates that the presence of these labels could furnish California I/M mechanics with accurate information for diagnosing and repairing late-model, high technology vehicles.

ARB staff's development of the content and format of the labels was undertaken through a committee of the Society of Automotive Engineers, which ARB staff members were instrumental in forming. The new regulations call for two machine-readable labels, one with the Vehicle Identification Number encoded (the VIN Label), and the other containing emission control information (the VEC label). The regulations cite the draft SAE standards: SAE J1892 for the VIN bar code, and SAE J1877 for the VEC code.

The VIN label will contain the bar-coded 17 character vehicle identification number required by Federal Motor Vehicle Safety Standard No. 115. This label would be separate from the VEC label, and installed in a location other than under the hood, the best location possibly being the driver's side door pillar.

The VEC label would be located under the hood and consist of 9 characters preceded by the data identifier "3T". The nine characters are defined as follows:

1, 2 Engine displacement in liters

The next five characters come from the 12-character Engine Family designation, including the same codes:

3 Vehicle and Fuel Type, e.g., V = Light Duty Gasoline Vehicle

4 Fuel metering type

5 Catalyst type

6, 7 Manufacturer-specific Engine Family Suffix

The last two characters describe emission control systems and engine idle speeds.

8 Emission Control System component combination

9 Ignition Frequency/Maximum Neutral Idle Speed

With the adoption of the new ARB regulations, a Smog Check inspection will be able to include reading with a light-wand both the VIN label and the VEC label. The combination of the two codes would identify the vehicle and the applicable emission standards exactly, and would deter mechanics from using the VEC from a different vehicle to test at less-stringent standards, according to the ARB staff. Reading these codes during I/M inspections will also allow accurate identification of those vehicles subject to emission control recall.

Including the catalyst type and the Engine Family designation will determine whether the vehicle is an open-loop or closed-loop system, and whether the system also includes an oxidizing catalyst. This should lead to better inspections, selection of the correct emission standards, and more accurate diagnoses and repairs.

Important information that could be subsequently added to the barcode includes the manufacturer's specifications for either exhaust oxygen or exhaust CO_2 content at idle and 2500 rpm. This information is vital to determining the overall state of the vehicle's mixture control system and air injection system, if installed, and to repairing them properly.

Another benefit of incorporating barcode reading capability into the TAS is that supplemental information could be provided for pre-1990 model vehicles, not factory-equipped with barcode labels. BAR could distribute a reference manual in which a barcode is provided for each make and model of vehicle subject to the program. Mechanics could look up the make and model being tested and use the bar code reading wand to enter a variety of information regarding the vehicle being tested.

Another approach might involve a one-time distribution of barcode stickers with registration renewal notices. Motorists could be instructed to take the barcode sticker with them when the vehicle is driven to a Smog Check station. The Smog Check station could affix the label next to the tuneup label.

Under either of these approaches, the validity of the barcode could be checked by the analyzer before it is used. The mechanic could first enter the make and model of the vehicle being tested and the barcode reader could then be passed over the barcode to determine whether the information contained in the barcode matches the vehicle description entered by the mechanic.

Another potentially valuable use of barcode is associated with the Certificates of Compliance that are issued by Smog Check stations. Currently, the number on each Certificate of Compliance is manually entered by the mechanic at the time that the Certificate is issued. The potential of keypunch errors frustrates the ability to match the reported Certificate number with the Certificate numbers submitted to the Department of Motor Vehicles. If each certificate number was in barcode form, both the Smog Check stations and DMV offices could read Certificate numbers quickly and efficiently. Subsequent data analysis could determine whether discrepancies exist.

One variation on this approach could be for the TAS to actually generate the Certificate of Compliance and print barcode on to it. Instead of purchasing books of Certificates from BAR, Smog Check stations could purchase a small floppy disk containing a unique list of Certificate numbers. The disk could also be encoded with the serial number(s) of the TAS owned by the Smog Check station. When inserted in the proper TAS, the disk would allow a certain number of Certificates to be printed by the TAS.

Repair Action Categories - As noted previously, there are seven possible repair actions that may be recorded using the current analyzer. They are "misfire", timing adjustment, air/fuel ratio adjustment, crankcase, fuel evaporative control system, a catch-all category called "exhaust control", and EGR. This limited number of categories has proven inadequate to determine what repairs were actually done or attempted. Based on the types of repairs that have proven effective in reducing emissions from vehicles that fail I/M tests, it is possible to generate a list of more detailed repair categories. Based on the I/M Evaluation Program and Radian's diagnosis of failures in late model vehicles, the list should include:

Ignition System Repairs
- spark plug replacement
- ignition wire repair or replacement
- timing adjustment
- other ignition repair

Intake System Repair
- air/fuel ratio adjustment
- carburetor rebuild or replacement
- other carburetor repair
- fuel injector cleaning or repair
- fuel injector replacement
- intake manifold replacement

Thermostatic Air Cleaner (TAC) vacuum lines
TAC flapper valve repair
TAC reconnection
other TAC repair
air filter housing repair
clean or replace air filter

PCV System Repair
PCV valve replacement
PCV valve reconnection
PCV hoses replacement
other PCV repair

Evaporative Control System Repair
canister replacement
vacuum line repair
other evaporative system repair

EGR System Repair
EGR valve cleaning
EGR valve replacement
other EGR repair

Sensors and Switches
O2 sensor
air flow sensor
coolant temperature sensor
air temperature sensor
throttle position sensor
crankshaft position sensor
manifold air pressure sensor
thermal vacuum switches
other sensors or switches

Fillpipe or Exhaust System Repair
exhaust manifold repair or replacement
exhaust pipe repair or replacement
catalyst replacement
lead restrictor replacement

Air Injection System Repair
air pump belt replacement
air pump repair or replacement
air reed valve repair or replacement
air injection plumbing repair or replacement
air injection diverter valve repair or replacement
air injection vacuum lines
other air injection system repair

Computer Repair

Miscellaneous Repairs
vacuum leaks
electrical system problems
cylinder head rebuild
new piston rings
other internal engine repair

Because of the substantial number of repair action categories listed above, the analyzer could be programmed to display detailed choices only when repairs in a general area have been identified.

Expert Systems Software - The proper diagnosis and repair of emission control system defects could be facilitated through the use of expert systems software. Incorporating expert systems software into the TAS is potentially the most effective implementation option for expert systems since, as explained in Section 5, it would substantially reduce the need for keyboard input by the mechanic. All information recorded on the TAS would be directly available to the expert system. In addition to increasing efficiency, integration would substantially improve the accuracy and consistency of information recorded by the TAS and the expert system.

Based on the survey of diagnostic equipment users described in the Appendix, diagnostic capabilities greater than those available from currently used systems are in demand. For maximum effectiveness, it should be possible to mimic the reasoning process of an expert mechanic/technician. An expert system computer program could be developed to accomplish this objective. Because automotive emissions control systems are highly variable and complex, the necessary software will be complicated and extensive. The software must embody:

- a compilation of all available information regarding the effectiveness of vehicle repairs;
- the ability to rapidly eliminate blind alleys;
- the capability to identify a change of course when new facts are uncovered (i.e., non-monotonic reasoning);
- the ability to consider a vast number of symptoms and recognize key problems;
- the ability to work with incomplete data and arrive at satisfactory results; and
- the ability to resolve problems that often defy neat, tractable solutions.

Although expert system software could be implemented through a "stand-alone" system, the vast amount of information which the program could need in order to reach proper conclusions regarding emission control system defects would make integration of the expert systems software with the Test Analyzer System a logical approach. (This, and other system concept options are discussed in the Section 5 of the report.)

In addition to guiding mechanics through diagnostic procedures, a Test Analyzer System containing expert systems software could record the result of the diagnosis and the after-repair emission test results. By analyzing the results of diagnoses and the after repair emission tests, it would be possible to get an indication of repair effectiveness (or lack thereof). The information could be used to update and refine the diagnostic procedures being directed by the expert system.

An expert system could also be a training aid for technicians. During the standard diagnostic test and the additional diagnostics, the analyzer could be programmed to show the reasoning used to perform specific diagnostics. By analyzing the reasoning, the technician would have the capability to improve his diagnostic capabilities.

The information which could be stored by the analyzer could be used to determine repair effectiveness, identify component failures which may require a recall, as well as improve diagnostic and repair procedures.

Miscellaneous TAS Modifications - In addition to the specific TAS changes discussed above, there are a number of features that would ensure the long-term viability of a new TAS design. These features include:

- the ability to have the data base updated frequently;
- the ability to add new visual inspection categories based on additional information or changes in control system designs;
- the ability to add new functional tests involving voltage or resistance measurements;
- the ability to add new tailpipe emission test modes (e.g., loaded mode testing) including NOx testing;
- the ability to provide automatic control for a chassis dynamometer;
- the ability to communicate with other computers.

There are hardware and software implications associated with these features. In terms of hardware, it would be desirable for the next generation TAS to be equipped with several communication ports reserved for future use. The industry standard RS-232 port is one option. Other hardware implications include the need for a high volume mass storage device with abundant reserve capacity. In addition, it would appear to be advantageous to have a consistent format for removable media so that the same media can be used to update analyzers produced by a variety of vendors.

In terms of software, the frequent updating of TAS systems would be most efficient if a consistent programming language and data file structure were used in all machines. Programming language consistency would appear to be especially important in the case of expert systems software where the high development costs make vendor-specific programs less practical.

Vehicle Test Record Implications

The possible TAS modifications discussed above imply substantial changes to the amount of information that would be stored for each test. Table 13 shows how all of the above mentioned TAS modifications might affect the data record format. Additions to the current format are shown in capital letters. Deletions are indicated by underlining.

In addition to a number of new inspection and repair action categories, there are several new response codes suggested in the table. In visual inspection categories, the added "V" response indicates a vacuum line related problem. "X" is intended to represent a malfunctioning device. Computer fault codes would be entered in two digit numbers. Repair action codes for sensors and switches would provide for responses indicating a wiring related problem ("W"), a vacuum line related problem ("V"), or a replacement ("R"). In addition, the "no" and "cost exceedance" responses would be retained.

Table 13

Proposed Changes to the California TAS
Vehicle Inspection Data Record Format

(Added Items Are in CAPITALIZED TYPE, Deleted Items are <u>Underlined</u>)

Field No.	Field Description	Field Length	Field Contents
1.	Station Number	8	alphanumeric
2.	TAS Number	5	alphanumeric
3.	Mechanic Number	9	alphanumeric
4.	Date of Test	6	MMDDYY (numeric)
5.	Test Start Time	4	HHMM (numeric)
6.	License/first VIN digits	8	alphanumeric
7.	Vehicle Type	1	P, L, M, H, <u>or T</u>

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Changes to TAS Record Format (continued)

Field No.	Field Description	Field Length	Field Contents
8.	GVW	5	numeric or unused
9.	Vehicle Make	4	alpha
10.	Vehicle Model Year	2	numeric
11.	Number of Cylinders	2	numeric
12.	Vehicle Engine Size	5	numeric followed by I, L, or C
NEW	BARCODE INFORMATION	≈100	ALPHANUMERIC
13.	Odometer Reading	4	100's of miles
14.	Test Type	1	I, B, A, or R
15.	Fuel Type	1	E, G, M, N, or P
Visual Inspection Results:			
16.	PCV System	1	P, D, M, S, or N + X
17.	Thermostatic Air Cleaner	1	P, D, M, S, or N + V OR X
18.	Air Injection PUMP	1	P, D, M, S, or N + V OR X
NEW	AIR PUMP BELT	1	P, D, X, OR N
NEW	PULSE AIR REED VALVES	1	P, D, M, S, or N + V OR X
NEW	AIR INJECTION LINES	1	P, D, M, S, or N + X
NEW	AIR DIVERTER VALVE	1	P, D, M, S, or N + V OR X
NEW	EXHAUST MANIFOLD	1	P, D, M, S, or N + X
NEW	INTAKE MANIFOLD	1	P, D, M, S, or N + X
19.	Fuel Evap. Controls	1	P, D, M, S, or N + V OR X
20.	Fillpipe Restrictor	1	P, D, M, S, or N
21.	Oxidation Catalyst	1	P, D, M, S, or N + X
22.	3-Way Catalyst	1	P, D, M, S, or N + X
23.	Exhaust Gas Recirculation	1	P, D, M, S, or N + V OR X
24.	Ignition Spark Control	1	P, D, M, S, or N + V OR X
NEW	O2 SENSOR (WIRING/LIGHT)	1	P, D, M, S, OR N + X
NEW	SENSORS/SWITCHES WIRING	1	P, D, M, S, OR N
NEW	SENSORS/SWITCHES VAC LINES	1	P, D, M, S, OR N
25.	Closed Loop Metering	1	P, D, M, S, or N
NEW	NO. OF COMPUTER FAULT CODES	1	0-9 NUMERIC
NEW	FAULT CODE #1	2	NUMERIC
NEW	FAULT CODE #2	2	NUMERIC
NEW	FAULT CODE #3	2	NUMERIC
NEW	FAULT CODE #4	2	NUMERIC
NEW	FAULT CODE #5	2	NUMERIC
NEW	FAULT CODE #6	2	NUMERIC
NEW	FAULT CODE #7	2	NUMERIC
NEW	FAULT CODE #8	2	NUMERIC
NEW	FAULT CODE #9	2	NUMERIC
26.	Carb. or Fuel Inj.	1	P, D, M, S, or N
27.	Other	1	P, D, M, S, or N

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Changes to TAS Record Format (continued)

Field No.	Field Description	Field Length	Field Contents
NEW	RECALL I.D. NUMBER 1	7	ALPHANUMERIC
NEW	RECALL I.D. NUMBER 2	7	ALPHANUMERIC
NEW	RECALL I.D. NUMBER 3	7	ALPHANUMERIC
NEW	RECALL I.D. NUMBER 4	7	ALPHANUMERIC
28.	Not Used SPARE	1	blank
29.	Not Used SPARE	1	blank
30.	Not Used SPARE	1	blank
NEW	SPARE	1	blank
NEW	SPARE	1	blank
MANUAL Functional Check Results:			
31.	Engine Warning Lights	1	P, F, or N
32.	Ignition Timing	1	P, F, or N
33.	Exhaust Gas Recirculation	1	P, F, or N
34.	Not Used PCV VALVE	1	blank P, F, OR N
35.	Not Used LEAD RESTRICTOR	1	blank P, F, OR N
NEW	SPARE	1	
NEW	SPARE	1	
NEW	SPARE	1	
NEW	SPARE	1	
NEW	SPARE	1	
AUTOMATED FUNCTIONAL CHECK RESULTS:			
NEW	O2 SENSOR TEST	1	P, R, L, OR N
NEW	FEEDBACK SYSTEM TEST	1	P, F, OR N
NEW	CATALYST EFFICIENCY TEST	1	P, F, OR N
NEW	SUPPLEMENTAL SENSOR TEST 1	1	P, F, OR N
NEW	SUPPLEMENTAL SENSOR TEST 2	1	P, F, OR N
NEW	SUPPLEMENTAL SENSOR TEST 3	1	P, F, OR N
NEW	SUPPLEMENTAL SENSOR TEST 4	1	P, F, OR N
NEW	SPARE	1	
NEW	SPARE	1	
NEW	SPARE	1	
NEW	SPARE	1	
NEW	SPARE	1	
36.	Standards Category	2	ALPHANUMERIC
37.	Previous High RPM HC	4	1 PPM units or blank
38.	Previous High RPM CO	4	.01% units or blank
39.	Previous Low RPM HC	4	1 PPM units or blank
40.	Previous Low RPM CO	4	.01% units or blank
41.	Current High RPM HC	4	1 PPM units
42.	Current High RPM CO	4	.01% units
43.	Current High RPM CO2	3	.1% units
NEW	HIGH RPM NOx	4	NUMERIC
NEW	HIGH RPM EXHAUST VOLUME	3	NUMERIC

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Changes to TAS Record Format (continued)

Field No.	Field Description	Field Length	Field Contents
44.	High RPM	4	numeric
45.	Current Idle RPM HC	4	1 PPM units
46.	Current Idle RPM CO	4	.01% units
47.	Current Idle RPM CO2	3	.1% units
NEW	IDLE RPM NOx	4	NUMERIC
NEW	IDLE RPM EXHAUST VOLUME	3	NUMERIC
48.	Idle RPM	4	numeric
NEW	SPARE HC MODE 1	4	NUMERIC
NEW	SPARE CO MODE 1	4	NUMERIC
NEW	SPARE CO2 MODE 1	3	NUMERIC
NEW	SPARE NOx MODE 1	4	NUMERIC
NEW	SPARE EXHAUST VOLUME 1	3	NUMERIC
NEW	SPARE RPM MODE 1	4	NUMERIC
NEW	SPARE HC MODE 2	4	NUMERIC
NEW	SPARE CO MODE 2	4	NUMERIC
NEW	SPARE CO2 MODE 2	3	NUMERIC
NEW	SPARE NOx MODE 2	4	NUMERIC
NEW	SPARE EXHAUST VOLUME 2	3	NUMERIC
NEW	SPARE RPM MODE 2	4	NUMERIC
NEW	SPARE HC MODE 3	4	NUMERIC
NEW	SPARE CO MODE 3	4	NUMERIC
NEW	SPARE CO2 MODE 3	3	NUMERIC
NEW	SPARE NOx MODE 3	4	NUMERIC
NEW	SPARE EXHAUST VOLUME 3	3	NUMERIC
NEW	SPARE RPM MODE 3	4	NUMERIC
49.	Test Results	1	P, F, or A
50.	Emission Reduction	1	R, N or blank
51.	Parts Cost	4	1 $ units or blank
52.	Labor Cost	4	1 $ units or blank
NEW	EXPERT SYSTEM PATH	≈100	NUMERIC
Repairs Performed:			
NEW	IGNITION SYSTEM REPAIR	1	Y OR N
53.	Misfire	1	Y, N, E
NEW	SPARK PLUG REPLACEMENT	1	Y, N, E
NEW	IGNITION WIRES REPAIR	1	Y, N, E
54.	Timing Adjustment	1	Y, N, E
NEW	IGN. SYSTEM VACUUM LINES	1	Y, N, E
NEW	OTHER IGNITION REPAIR	1	Y, N, E
NEW	INTAKE SYSTEM REPAIR	1	Y OR N
55.	A/F Ratio Adjustment	1	Y, N, E
NEW	CARBURETOR REBUILD/REPL.	1	Y, N, E
NEW	OTHER CARBURETOR REPAIR	1	Y, N, E
NEW	FUEL INJ. CLEAN OR REPAIR	1	Y, N, E

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Changes to TAS Record Format (continued)

Field No.	Field Description	Field Length	Field Contents
NEW	FUEL INJECTOR REPLACEMENT	1	Y, N, E
NEW	REPLACE INTAKE MANIFOLD	1	Y, N, E
NEW	TAC VACUUM LINES	1	Y, N, E
NEW	TAC FLAPPER VALVE REPAIR	1	Y, N, E
NEW	TAC RECONNECTION	1	Y, N, E
NEW	OTHER TAC REPAIR	1	Y, N, E
NEW	AIR FILTER HOUSING REPAIR	1	Y, N, E
NEW	AIR FILTER CLEAN/REPLACE	1	Y, N, E
NEW	PCV SYSTEM REPAIR	1	Y OR N
56.	Crankcase PCV VALVE REPL.	1	Y, N, E
NEW	PCV VALVE RECONNECTION	1	Y, N, E
NEW	NEW PCV HOSES	1	Y, N, E
NEW	OTHER PCV REPAIR	1	Y, N, E
NEW	EVAPORATIVE SYSTEM REPAIR	1	Y OR N
57.	Fuel Evap. CANISTER REPL.	1	Y, N, E
NEW	EVAP VACUUM LINE REPAIR	1	Y, N, E
NEW	OTHER EVAP SYSTEM REPAIR	1	Y, N, E
NEW	EGR SYSTEM REPAIR	1	Y OR N
58.	Exhaust Control	1	Y, N, E
NEW	EGR VALVE CLEANING	1	Y, N, E
59.	EGR VALVE REPLACEMENT	1	Y, N, E
NEW	EGR VACUUM LINE REPAIR	1	Y, N, E
NEW	OTHER EGR SYSTEM REPAIR	1	Y, N, E
NEW	SENSORS AND SWITCHES	1	Y OR N
NEW	O2 SENSOR	1	W, V, R, N, E
NEW	AIR FLOW SENSOR	1	W, V, R, N, E
NEW	COOLANT TEMP SENSOR	1	W, V, R, N, E
NEW	AIR TEMP SENSOR	1	W, V, R, N, E
NEW	THROTTLE POSITION SENSOR	1	W, V, R, N, E
NEW	CRANKSHAFT POSITION SENS.	1	W, V, R, N, E
NEW	MANIFOLD AIR PRESS. SENS.	1	W, V, R, N, E
NEW	THERMAL VACUUM SWITCH	1	W, V, R, N, E
NEW	OTHER SENSOR	1	W, V, R, N, E
NEW	FILLPIPE OR EXHAUST SYSTEM	1	Y OR N
NEW	EXH. MANIFOLD REPAIR/REPL.	1	Y, N, E
NEW	EXH. PIPE REPAIR/REPLACE	1	Y, N, E
NEW	CATALYST REPLACEMENT	1	Y, N, E
NEW	LEAD RESTRICTOR REPLACEMENT	1	Y, N, E
NEW	AIR INJECTION SYSTEM	1	Y OR N
NEW	AIR PUMP BELT REPLACEMENT	1	Y, N, E

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Changes to TAS Record Format (continued)

Field No.	Field Description	Field Length	Field Contents
NEW	AIR PUMP REPAIR/REPLACE	1	Y, N, E
NEW	AIR REED VALVE REPAIR/REPL.	1	Y, N, E
NEW	AIR INJECTION PLUMBING	1	Y, N, E
NEW	AIR INJ. DIVERTER VALVE	1	Y, N, E
NEW	AIR INJ. VACUUM LINES	1	Y, N, E
NEW	OTHER AIR INJ. SYS. REPAIR	1	Y, N, E
NEW	COMPUTER REPLACEMENT	1	Y, N, E
NEW	MISCELLANEOUS REPAIRS	1	Y OR N
NEW	VACUUM LEAKS	1	Y, N, E
NEW	ELECTRICAL SYSTEM PROBLEMS	1	Y, N, E
NEW	CYLINDER HEAD REBUILD	1	Y, N, E
NEW	NEW PISTON RINGS	1	Y, N, E
NEW	OTHER INTERNAL ENGINE REP.	1	Y, N, E
NEW	SPARE	1	Y, N, E
NEW	SPARE	1	Y, N, E
NEW	SPARE	1	Y, N, E
NEW	SPARE	1	Y, N, E
NEW	SPARE	1	Y, N, E
60.	Exceeds Cost Limit	4	1 $ units or blank
61.	Not Used	7	blank
62.	Certificate Number	9	alphanumeric
63.	Escape Code #4	2	numeric
64.	Escape Code #3	2	numeric
65.	Escape Code #2	2	numeric
66.	Escape Code #1	2	numeric
67.	Tampering	1	X, C, T, or blank
68.	Test End Time	4	HHMM
	OLD TOTAL	183	
	NEW TOTAL	462	

7. POTENTIAL EMISSION BENEFITS AND COST/EFFECTIVENESS

Accurately estimating the cost effectiveness of expert systems and other TAS enhancements is difficult because there are so many factors that affect the emission reductions achievable under the Smog Check program. Emission reductions depend on the effectiveness with which defects are identified and repaired. The primary benefit of an expert system would be in defect identification. However, with late model vehicles, repair of identified defects usually consists of a relatively straightforward component replacement. Identification of defects is the critical requirement.

Estimated Emission Benefits

Based on the I/M Evaluation program conducted during 1985 and 1986, the overall efficiency with which mechanics identified defects was 25%. By forcing mechanics to perform certain diagnostic tests in response to expert system programming, many of the unidentified defects could be corrected. (This assumes that mechanics are required to perform diagnostic tests by virtue of the integration of expert systems software with the rest of the TAS.) Based on the effectiveness of the diagnostic tests for oxygen sensors, feedback controls, and catalysts, it is apparent that most of these types of critical defects could be detected through the use of expert systems software in conjunction with other TAS upgrades. Air pump defects would also be more likely to be identified because the data base for the expert system could include information on the expected CO plus CO_2 concentration in the exhaust of specific vehicle models when the air pump system is functioning properly.

However, it is possible that mechanic performance will be improved through increased enforcement efforts before expert systems can be implemented. In the evaluation of the Smog Check program improvements conducted under the I/M Evaluation Program, it was estimated that defect identification could increase from 25% to 68% if each mechanic performed at his or her level of capability. Assuming this performance increase is achieved through BAR enforcement action, the benefits of expert systems use and other TAS upgrades would be restricted to 32% of the defects which would otherwise not be identified.

A first order approximation for the potential benefits of an enhanced TAS was based on the assumption that just one half of this remaining 32% of unidentified defects would be detected and corrected. The emissions impact of the defects currently not corrected in the Smog

Check program were estimated in the April 1987 report to the Legislature. They are shown in Table 14.

Table 14

Theoretical Benefits of
Improving the Smog Check Program
(percent of baseline emissions that could be eliminated)

	HC	CO	NOx
Eliminate All Tampering of Exhaust Emission Controls	16.6%	10.7%	10.9%
Repair Non-Tampering Exhaust Emission Defects	6.4%	5.2%	9.4%
Fix PCV Tampering & Defects	7.0%	-	-
Total Potential Benefits	30.0%	15.9%	20.3%
16% of Potential Benefits	4.8%	2.5%	3.2%

As shown in the table, the potential benefits of additional defect correction are 30% for HC, 15.9% for CO and 20.3% for NOx. If TAS enhancements are able to accomplish 16% of these benefits, the additional emission reductions achieved by the Smog Check program will be 4.8% for HC, 2.5% for CO and 3.2% for NOx.

Estimated Cost

The estimated cost of the TAS enhancements considered are shown in Table 15. The table lists the estimated costs for hardware changes needed to implement the TAS modifications considered in this report. All costs were estimated based on a 10% markup of projected wholesale prices for greater than 1,000 units. (Most component prices are based on quotes supplied by JDR Microdevices of San Jose, California.) As the table shows, the net cost increase for the recommended TAS hardware changes is $735.

During a BAR workshop with TAS vendors, several comments were made to the effect that a 10% markup was substantially lower than would normally be charged. Although not specifically mentioned by TAS vendors, it should also be noted that there was no cost assigned to the amortization of the system development and retooling costs for a new TAS. However, the cost estimate presented in Table 15 assumes no cost reduction associated with the components of the current TAS that would be incorporated in the new system. Since the development and tooling cost for the current TAS has probably already been amortized,

Table 15

Estimated Costs for Recommended TAS Changes

Standardized CPU w/640 KB RAM	$160
High Capacity Fixed Media w/controller	260
3.5 Inch Floppy Disk w/controller	155
Parallel and Serial Communication Ports	60
Bar Code Wand, Spark Interrupter, 02 Sensor/Multi-Meter Leads	350
Subtotal, new hardware	$985
Deletions - Cassette Recorder, CPU, Memory	$250
Net Hardware Cost	$735
Expert Systems Software Development (amortized over 8,000 TASs)	$125
Total Cost Increase	$860
Cost of Current TAS	$7,500
Estimated Cost of New TAS	$8,360
Increased Cost per Test (amortized over 5 years @10%)	$1.45

and since they are included in the price assumed for the "current" TAS, the amortization of additional development costs would be "double counting" this cost factor. Our analysis of system cost is clearly a first-order estimate, however, a 100% increase in the cost of the modifications needed for the current TAS would change the system cost estimate by only 10%. It does not appear that the uncertainty regarding the preliminary cost analysis will substantially affect the cost-effectiveness of the comprehensive set of TAS changes proposed.

The cost estimate shown in Table 15 is based on the assumption that standard personal computer hardware would be acceptable for use in garage-based TASs. During a workshop with TAS vendors held by BAR, the durability of hard disk drives in this environment was questioned by some vendors. The concern was raised that movement of the TAS would introduce unacceptably high shock loads. Since hard disk drives have been successfully employed in portable PCs, it is not clear that a fundamental durability problem would exist. It may be possible to adequately insulate the drive from shock loading. However, some vendors expressed the concern that this problem could be so serious as to make the integration of an expert system with the TAS infeasible.

In response to the concerns that were raised, Sierra investigated the possibility that more durable mass storage media could be utilized. Based on consultation with representatives of IOMEGA Corporation of South Roy, Utah, it appears that an alternative mass storage device, called a Bernoulli Box, would be an option available to TAS vendors. The Bernoulli drive is really a very high quality floppy disk technology. 20 megabytes can be stored on a 5 1/4 inch removable cartridge.

Representatives of IOMEGA provided Sierra with the following shock specifications (in G's) for the drive:

<u>Operating</u>

3.0 for 20ms
0.85 @ 5-17 Hz
0.25 @ 17-500 Hz

<u>Quiescent</u>

40.0 for 15ms
1.3 @ 5-27 Hz
2.0 @ 27-60 Hz
5.0 @ 60-500 Hz

The actual durability of the drive reported to Sierra would appear to exceed these specifications. Representatives of IOMEGA report successful mobile applications include passenger vans and military "jeep" vehicles. It was also reported that the drive can be dropped onto a hard surface from a height of one foot without damage.

Approximately 10,000 Bernoulli drives are currently in customer service. The 20 megabyte drive has a list retail price of $1,300, however, OEM discounts are in the range of 35-40%. Given the volumes associated with Test Analyzer Systems, Sierra expects that discounts would be further increased. List price for the cartridges used in the drives is $83 in very low purchase volumes. Although the use of

Bernoulli drives instead of conventional hard disks would appear to increase system costs by about $400-500, this would be only about 5% of total projected TAS cost, and may not be necessary.

As shown in Table 15, software costs are estimated to increase by $125 per unit. This estimate is based on the assumption that expert system software is developed by one organization, at a cost of $1 million, and shared among all vendors. It is difficult to estimate the cost of an expert system that would cover the majority of the vehicles with electronic control systems. The expert system that Radian developed to cover some of the problems in the electronic control system of General Motors vehicles took approximately 100 staff-hours to develop. This expert system covers approximately 10 percent of the General Motors vehicles in customer use with electronic control systems. Furthermore, it covers about 20 percent of the problems in those particular vehicles. Assuming that on a vehicle make basis General Motors accounts for about 25 percent of the vehicles, the prototype expert system would account for about a half percent of the effort to develop an expert system for vehicle diagnosis. Consequently, the development of an expert system to cover most vehicles sold with electronic control systems would be about 200 times greater than the effort required for the prototype expert system, or approximately 20,000 staff-hours. This would translate into an approximate cost of $1,000,000. However, expert systems can be developed to solve the most significant problems leading to excess emissions for much lower costs, for example, between $250,000 and $500,000 dollars.

Total system cost for the enhanced TAS is estimated at $860 above the BAR'84 systems. Using an estimate for the cost of a current generation (BAR'84) TAS of $7,500 dollars, the total cost for the proposed new TAS would be $8,360. Amortizing the $8,360 cost over a five year period with a 10% interest rate would result in an annualized cost of $2,174 per TAS system. Assuming 8,000 TASs are used in the program and approximately 1 million tests are conducted each month, the cost per test increase associated with the higher cost TAS would be $1.45.

Table 16 shows a cost effectiveness estimate for the current Smog Check program. As the table shows, the average inspection fee of $20 per vehicle is divided by two to determine the annual cost of inspections under a biennial program. Likewise, the $6 Certificate fee is divided in two. The average repair cost of $35 is applied to the 33% of the vehicles that fail the test and divided by two to put it on an annual basis. 50% of total I/M costs are allocated to HC and NOx. (The remainder to carbon monoxide.) As shown in the I/M Review Committee's report to the Legislature, baseline emissions of 2.11 g/mi HC are reduced by 12% and baseline NOx emissions of 1.55 g/mi are reduced by 4%. Based on an estimated 9,894 miles per year of vehicle travel, the overall cost effectiveness of the current program is estimated at $1.48 per pound of HC plus NOx.

Table 16

Cost Effectiveness Calculations
For Current Private Garage I/M Program
(Biennial Inspections)

Basic inspection fee ($20÷2)		$10
Program Administration/Enforcement/Referee ($6÷2)		3
Average repair cost ([$35×0.33]÷2)		6
Total annual cost		$19
50% of Total annual cost allocated to HC+NOx		$10
Baseline emission level, HC	2.11 g/mi	
12% HC reduction		0.25 g/mi
Baseline emission level, NOx	1.55 g/mi	
4% NOx reduction		0.06 g/mi
HC+NOx emission reduction		0.31 g/mi
Average annual travel		× 9,894 miles
Total grams HC+NOx reduction per vehicle per year		3,067 grams

Cost Effectiveness (HC+NOx) =
$10 ÷ 3,067 g = $1.48/lb. = $2,960/ton

Table 17 shows the <u>incremental</u> cost effectiveness calculation for the enhanced TAS. As noted above, the inspection fee is estimated to increase by $1.45. The average cost of <u>additional</u> repairs has been conservatively estimated to be $100 per failed vehicle and 11% of all tested vehicles (one-third of those which currently fail) are estimated to receive additional repairs. Using Mobile3 and EMFAC emissions simulation models*, calendar year 2000 baseline emission rates have been estimated so as not to overstate the potential benefits of enhanced TASs by using emission rates for the current

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* MOBILE3 projections were taken from Sierra's January 1988 report, "The Feasibility and Costs of More Stringent Mobile Source Controls". They reflect the implementation of a 0.25 g/mi NMHC standard and a 0.4 g/mi NOx standard in 1990. EMFAC projections were obtained from ARB's comments on the Sierra report and appear to represent the combination of a 0.39 NMHC standard and a 0.4 NOx standard.

fleet. With 4.8% more HC reductions and 3.2% more NOx reductions, the cost effectiveness of TAS enhancements is estimated at $1.59-2.85 per pound of HC plus NOx. This compares quite favorably with the cost effectiveness of other emissions control measures already adopted.

Table 17

Incremental Cost Effectiveness Calculations
For Use of Improved TAS

(Biennial Program - Year 2000 Fleet)

(Range Shown Reflects Difference
Between MOBILE3 and EMFAC Projections)

Basic inspection fee increase ($1.45÷2)	$ 0.72
Average repair cost increase ([$100×0.11]÷2)	5.50
Total annual cost increase	$6.22
50% of Total annual cost allocated to HC+NOx	3.11
Baseline emission level, HC	0.70-1.18 g/mi
4.8% additional HC reduction	0.03-0.06 g/mi
Baseline emission level, NOx	0.76-1.09 g/mi
3.2% additional NOx reduction	0.02-0.03 g/mi
HC+NOx emission reduction	0.05-0.09 g/mi
Average annual travel	× 9,894 miles
Total grams HC+NOx reduction per vehicle per year	495-890 grams

Cost Effectiveness (HC+NOx) =
$3.11 ÷ (495-890 g) = $1.59-2.85/lb. = $3,173-5,700/ton

Appendix

Detailed Results of
Diagnostic Equipment User Survey

Smog Check Station 1

Analyzer Make: <u>Allen Smartscope</u>

Approximate percentage of repairs for which the equipment is used? <u>100%</u>

Do you use the analyzer to diagnose problems with computer controlled vehicles? <u>YES</u>

Is the diagnostic information presented by the analyzer accurate? <u>YES, BUT IT HAS TO BE INTERPRETED PROPERLY, IT GIVES YOU AREAS TO LOOK AT</u>

Does the analyzer encourage short-cutting of diagnostic procedures? <u>NOT REALLY THERE IS NOT A LOT YOU CAN SHORT-CUT; YOU'VE GOT TO GO BY THE NUMBERS OR FORGET IT, YOU'LL GET LOST</u>

Is the equipment worth its cost? <u>YES AND NO, MAINTENANCE PROBLEMS AND MALFUNCTIONS HAVE CAUSED THE COSTS TO BE MORE THAN ANTICIPATED</u>

What modifications would you make to improve the equipment? <u>NO MAJOR CHANGES TO THE ALLEN MACHINE, EACH MACHINE HAS ITS OWN DOWNFALLS. ONE THING I'VE NEVER LIKED IS THAT YOU CAN'T USE THE TIMING LIGHT WITHOUT CHANGING THE SET-UP ON THE MACHINE</u>

<u>THE GOOD THING ABOUT THE ALLEN MACHINE IS IT IS A SELLING FEATURE FOR MY CUSTOMERS, THEY LIKE THE PRINTOUTS; IT BUILDS THE MECHANICS CONFIDENCE</u>

Smog Check Station 2

Analyzer Make: SUN INTERROGATOR 2

Approximate percentage of repairs for which the equipment is used?
100%

Do you use the analyzer to diagnose problems with computer controlled vehicles? NO

Is the diagnostic information presented by the analyzer accurate?
NO, THE INTERROGATOR IS A SALES PROMOTION TOOL, IT DOES NOT PRESENT TECHNICAL INFORMATION

Does the analyzer encourage short-cutting of diagnostic procedures?
NO, IT TIES YOU INTO A FAULT TREE THAT YOU MUST FOLLOW

Is the equipment worth its cost? NO, I WOULD NEVER SUGGEST TO ANYONE THAT THEY SHOULD BUY THIS MACHINE. ALL YOU NEED IS A GOOD MANUAL SCOPE AND SOMEONE WITH THE ABILITY TO WORK

What modifications would you make to improve the equipment? A COMPUTER IS GOOD FOR THE GUY WHO LACKS KNOWLEDGE, SOMEONE WITH KNOWLEDGE ONLY NEEDS A GOOD OSCILLOSCOPE WITH A MILLESECOND SWEEP. I WOULDN'T MAKE ANY CHANGES TO A BASIC OSCILLOSCOPE

Smog Check Station 3

Analyzer Make: ALLEN SMART SCOPE

Approximate percentage of repairs for which the equipment is used? CAN'T SAY

Do you use the analyzer to diagnose problems with computer controlled vehicles? YES

Is the diagnostic information presented by the analyzer accurate? YES

Does the analyzer encourage short-cutting of diagnostic procedures? NO, YOU MUST GO BY THE BOOK

Is the equipment worth its cost? NOT SURE

What modifications would you make to improve the equipment? NONE

Smog Check Station 4

Analyzer Make: ALLEN SMART SCOPE

Approximate percentage of repairs for which the equipment is used? 30%

Do you use the analyzer to diagnose problems with computer controlled vehicles? YES

Is the diagnostic information presented by the analyzer accurate? YES, BUT IT DOESN'T TELL YOU MUCH

Does the analyzer encourage short-cutting of diagnostic procedures? FOR ELECTRICAL MISFIRES AND OTHER STUFF

Is the equipment worth its cost? YES

What modifications would you make to improve the equipment? HAVE THE ANALYZER EXACTLY PINPOINT PROBLEMS ON COMPUTER CONTROLLED VEHICLES, CURRENT ANALYZERS ONLY TELL YOU TO CHECK THIS OR THAT WHICH YOU WOULD HAVE TO DO ANYWAY

Smog Check Station 5

Analyzer Make: ALLEN SMART SCOPE

Approximate percentage of repairs for which the equipment is used?
80%

Do you use the analyzer to diagnose problems with computer controlled vehicles? YES

Is the diagnostic information presented by the analyzer accurate?
YES

Does the analyzer encourage short-cutting of diagnostic procedures?
I DO NOT FEEL IT ENCOURAGES SHORT-CUTTING, I ALWAYS PERFORM A VISUAL INSPECTION

Is the equipment worth its cost? YES

What modifications would you make to improve the equipment? MAKE THE EXHAUST GAS ANALYZER A LITTLE MORE ACCURATE, THERE IS A DIFFERENCE BETWEEN THE READINGS WHEN THE MACHINE IS IN THE TUNE-UP MODE AND THE ACTUAL SMOG CHECK TEST. THE RESULTS FROM THE TUNE-UP MODE ARE PASSING, BUT WHEN THE SMOG CHECK IS PERFORMED, THE VEHICLE FLUNKS

Smog Check Station 6

Analyzer Make: BEAR ACE

Approximate percentage of repairs for which the equipment is used? 75%

Do you use the analyzer to diagnose problems with computer controlled vehicles? FOR SOME VEHICLES YES, ON OTHERS WE USE A HAND-HELD COMPUTER ANALYZER

Is the diagnostic information presented by the analyzer accurate? YES, THE BEAR IS A VERY GOOD MACHINE

Does the analyzer encourage short-cutting of diagnostic procedures? NO

Is the equipment worth its cost? DON'T KNOW

What modifications would you make to improve the equipment? NONE

Smog Check Station 7

Analyzer Make: SUN INTERROGATOR 2

Approximate percentage of repairs for which the equipment is used? 15%

Do you use the analyzer to diagnose problems with computer controlled vehicles? NO

Is the diagnostic information presented by the analyzer accurate? NO, THE ANALYZER WON'T PICK UP A BLOWN HEAD-GASKET BY STICKING THE PROBE IN THE RADIATOR

Does the analyzer encourage short-cutting of diagnostic procedures? NO

Is the equipment worth its cost? NO

What modifications would you make to improve the equipment? THE DIAGNOSTIC INFORMATION TELLS YOU NOTHING, IT TELLS YOU TO CHECK 20 DIFFERENT THINGS WHICH MAY BE WRONG

Smog Check Station 8

Analyzer Make: ALLEN SMART SCOPE

Approximate percentage of repairs for which the equipment is used? 99%

Do you use the analyzer to diagnose problems with computer controlled vehicles? NO, WE DON'T GET INTO THAT MUCH, BUT IF WE DO WE USE THE ANALYZER

Is the diagnostic information presented by the analyzer accurate? YES

Does the analyzer encourage short-cutting of diagnostic procedures? YES IT DOES

Is the equipment worth its cost? YES

What modifications would you make to improve the equipment? ADD ADDITIONAL DIAGNOSTICS

Smog Check Station 9

Analyzer Make: BEAR ACE

Approximate percentage of repairs for which the equipment is used? 100%

Do you use the analyzer to diagnose problems with computer controlled vehicles? NO, WE USE AN OTC HAND-HELD COMPUTER ANALYZER

Is the diagnostic information presented by the analyzer accurate? YES, IT IS VERY ACCURATE

Does the analyzer encourage short-cutting of diagnostic procedures? YES, IT GIVES MORE ACCURATE READINGS WITHOUT GOING THROUGH THE PROCESS OF ELIMINATION

Is the equipment worth its cost? YES

What modifications would you make to improve the equipment? NONE

Smog Check Station 10

Analyzer Make: BEAR ACE

Approximate percentage of repairs for which the equipment is used? 30%

Do you use the analyzer to diagnose problems with computer controlled vehicles? NO, USE A DIFFERENT HAND-HELD TOOL TO ANALYZE COMPUTER PROBLEMS

Is the diagnostic information presented by the analyzer accurate? YES

Does the analyzer encourage short-cutting of diagnostic procedures? NO

Is the equipment worth its cost? IT'S HARD TO SAY

What modifications would you make to improve the equipment? NONE PERSONNALLY, I'VE WORKED WITH OTHER SCOPES THAT I DID NOT FEEL PROVIDED SUFFICIENT DIAGNOSTIC INFORMATION

Smog Check Station 11

Analyzer Make: ALLEN SMART SCOPE

Approximate percentage of repairs for which the equipment is used?
CAN'T SAY

Do you use the analyzer to diagnose problems with computer controlled vehicles?

Is the diagnostic information presented by the analyzer accurate?
YES

Does the analyzer encourage short-cutting of diagnostic procedures?
NO

Is the equipment worth its cost? NO, NONE OF IT IS

What modifications would you make to improve the equipment? A FASTER PRINTER

Smog Check Station 12

Analyzer Make: SUN, BUT NOT THE INTERROGATOR

Approximate percentage of repairs for which the equipment is used?
30% TO 40%

Do you use the analyzer to diagnose problems with computer controlled vehicles? OCCASSIONALLY

Is the diagnostic information presented by the analyzer accurate?
YES

Does the analyzer encourage short-cutting of diagnostic procedures?
NO

Is the equipment worth its cost? YES

What modifications would you make to improve the equipment? NONE

Smog Check Station 13

Analyzer Make: ALLEN SMART SCOPE

Approximate percentage of repairs for which the equipment is used?
10%

Do you use the analyzer to diagnose problems with computer controlled vehicles? SOMETIMES, HALF THE TIME WE USE A HAND-HELD ANALYZER

Is the diagnostic information presented by the analyzer accurate?
70% OF THE TIME

Does the analyzer encourage short-cutting of diagnostic procedures?
NO

Is the equipment worth its cost? INITIAL COST YES, BUT THE MAINTENANCE COSTS ARE A KILLER

What modifications would you make to improve the equipment? MAKE THEM MORE RELIABLE, BETTER FILTRATION UNITS SO THEY DON'T GET CLOGGED WITH DIRT AND REQUIRE PUMP AND BOARD REPLACEMENT

Smog Check Station 14

Analyzer Make: SUN NOT THE INTERROGATOR

Approximate percentage of repairs for which the equipment is used?
100%

Do you use the analyzer to diagnose problems with computer controlled vehicles?

Is the diagnostic information presented by the analyzer accurate?
YES, AS ACCURATE AS THE MECHANIC USING THE ANALYZER

Does the analyzer encourage short-cutting of diagnostic procedures?
NO

Is the equipment worth its cost? YES

What modifications would you make to improve the equipment? NONE

Smog Check Station 15

Analyzer Make: NONE, NO LONGER A SMOG CHECK STATION

Approximate percentage of repairs for which the equipment is used?

Do you use the analyzer to diagnose problems with computer controlled vehicles?

Is the diagnostic information presented by the analyzer accurate?

Does the analyzer encourage short-cutting of diagnostic procedures?

Is the equipment worth its cost?

What modifications would you make to improve the equipment?

Smog Check Station 16

Analyzer Make: AN OLDER ALLEN, A DINOSAUR WHICH IS NOT COMPUTER CONTROLLED WE ONLY WORK ON OLD BRITISH CARS AND PERFORM SMOG CHECKS AS A SERVICE FOR OUR REGULAR CUSTOMERS

Approximate percentage of repairs for which the equipment is used?

Do you use the analyzer to diagnose problems with computer controlled vehicles?

Is the diagnostic information presented by the analyzer accurate?

Does the analyzer encourage short-cutting of diagnostic procedures?

Is the equipment worth its cost?

What modifications would you make to improve the equipment?

Smog Check Station 17

Analyzer Make: SUN, BUT NOT THE INTERROGATOR

Approximate percentage of repairs for which the equipment is used?
100%

Do you use the analyzer to diagnose problems with computer controlled vehicles? YES

Is the diagnostic information presented by the analyzer accurate?
YES, ALTHOUGH I ONCE HAD A SMART SCOPE, IT WAS A WASTE OF TIME AND I SOLD IT

Does the analyzer encourage short-cutting of diagnostic procedures?
NO

Is the equipment worth its cost? YES, ITS PAID FOR

What modifications would you make to improve the equipment? NEEDS A BRIGHTER TIMING LIGHT, AND DO AWAY WITH THE MAGNETIC TIMING PROBE

A Study of Excess Motor Vehicle Emissions - Causes and Control

Section V

Evaluation of Factors Affecting Catalyst Durability In Light-Duty Vehicles

prepared for:

State of California Air Resources Board

prepared by:

Sierra Research, Inc.
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Sacramento, California 95814
(916) 444-6666

SECTION V

A STUDY OF EXCESS MOTOR VEHICLE EMISSIONS - CAUSES AND CONTROL

Evaluation of Factors Affecting Catalyst Durability In Light-Duty Vehicles

prepared for:

California Air Resources Board

December 1988

prepared by:

Sierra Research, Inc.
1521 I Street
Sacramento, CA 95814

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1.0 SUMMARY AND CONCLUSIONS

An evaluation of the factors affecting automotive exhaust catalyst durability indicates that there are a number of conditions experienced in customer service that can lead to greater catalyst deterioration than occurs during the 50,000 mile certification test. There is clear evidence that many catalysts experience greater thermal stress in customer service than under the relatively moderate driving cycle specified for the certification durabaility test. In addition, greater amounts of chemical poisoning of the catalyst can occur in customer service due to differences in gasoline and oil specifications.

1.1 Thermal Degradation

Catalyst and automobile manufacturers appear to disagree over the threshold temperature at which catalyst damage begins to occur. Auto industry sources maintain that the threshold temperature is 1,400°F. Catalyst manufacturers suggest that it is in the range of 1,600 - 1,800°F and point towards recently developed catalysts for European vehicles and heavy-duty trucks as proof of the ability of the new catalysts to perform in the higher temperature environments. Catalyst manufacturers, however, were not able to provide data documenting the ability of new catalyst formulations to withstand 1,600 - 1,800°F temperatures without deterioration.

The ability of catalysts to withstand temperatures above 1,400°F is an important issue, because 1,400°F is typically the highest temperature experienced under normal driving conditions. (Higher temperatures can be experienced under certain modes of operation.) Whether the higher temperatures will degrade catalyst performance is currently a point of controversy between vehicle manufacturers and catalyst vendors. Conversations with catalyst manufacturers indicated that a new "high tech" generation of more durable catalysts was introduced in 1985. Most of the data in the literature and collected in this study address the performance of pre-1985 vehicles/catalysts. As data become available on the performance of the "high tech" catalysts, it is suggested that a substantial reduction in degradation will be noted. With the existing data it is not possible to determine whether 1,400°F or some higher temperature is the threshold at which degradation begins to occur; however, the following conclusions can be reached:

- The threshold for catalyst damage is lower under lean conditions than it is under rich conditions. Lean high temperature excursions have been shown to significantly affect rhodium interactions with alumina, and platinum and cerium oxide crystal growth. The primary impact of these interactions is a loss of CO and NOx conversion efficiencies at and rich of stoichiometry.

- The trend towards exclusive use of MPFI systems with single-bed three-way catalysts and elimination of secondary air is significantly reducing the chances of lean high temperature occurrences. It is also places increasing reliance on rhodium for the conversion efficiency of all three pollutants.

- The primary cause of thermal deterioration is lean misfire which can elevate catalyst temperatures to above 2,000°F. No data are available to quantify the frequency with which these conditions occur.

- The AMA cycle has been shown to produce catalyst temperatures that are not representative of in-use driving conditions. The lack of thermal stress on the durability test could be a significant source of the difference in deterioration experienced between certification and well-maintained vehicles. The representativeness of the temperatures that catalysts experience on the durability cycle needs to be improved.

- The representativeness of the durability temperatures could become more important as manufacturers move catalysts closer to the engine to comply with more stringent emission standards (e.g., the 0.25 gm/mi HC standard being considered by ARB). By reducing the distance from the engine to the catalyst the time required to achieve "light-off" will be decreased and the catalyst will convert a larger portion of the emissions generated under cold start conditions.

- To improve the representativeness of the thermal stress that catalysts receive on the durability cycle, engine loads would need to be increased. The options to accomplish this include test track or dynamometer mileage accumulation with high vehicle cargo loads and higher speeds.

- The collection of data characterizing temperatures that catalysts experience under in-use conditions and on AMA cycles is needed to support the development of improvements to the AMA cycle. It would produce a better understanding of the causes of deterioration that well-maintained vehicles experience under in-use conditions. It could also be used to aid decisions about the ability of manufacturers to achieve more stringent emission standards.

1.2 Chemical Poisoning

The available data presented suggest that the primary poisons that affect catalyst durability are the trace lead levels contained in both leaded and unleaded gasoline and the phosphorus contained in engine oil antiwear/antioxidant additives. The remainder of the suspected poisons have been shown to have little effect on catalyst durability because either: the effects are reversible, as in the case of sulfur; the effects are not relevant because of the absence of contamination as in the case of manganese; or the effects are significant but the level of fuel contamination is extremely small and poorly documented, as in the case of silicon.

It is difficult to compare the effects of lead and phosphorus because of the poor documentation of alternative phosphorous level effects. Several studies noted catalyst retention of phosphorus is the greatest of any of the deposit constituents. That finding must be tempered by the fact that phosphorus is a "non-specific" poison in that it does not seek active metal sites for deposition. Instead, its deposition is influenced by flow rates, surface geometry and temperature gradients. Given the large surface areas in the catalyst that do not contain active metals, the effect of this deposition is reduced. In contrast, lead is a "specific" poison in that it is selectively deposited directly on active metal sites as HC is oxidized. Thus, small amounts of lead can exert a significant impact on catalyst activity.

The survey of the lead levels of unleaded gasoline shows that levels have been declining since 1979 and that the lowest recorded level was in 1987 with 1 mg/gal. Nevertheless, a Ford analysis showed that trace levels of 1 mg/gal can have a 10 percent effect on catalyst performance in approximately 5,000 miles. Because of the extreme toxicity of lead to catalyst performance, ARB should consider setting a target for the complete elimination of lead from unleaded gasoline and work with refiners to achieve that goal. The effect of such a program, even if it is phased-in over an extended period of time, will be to eliminate a significant source of long-term, low-level catalyst deterioration.

The confusion over the mechanisms of engine-oil-based phosphorous poisoning and the dearth of information on the effects of alternative phosphorous levels on catalyst performance makes it difficult to target a specific reduction in phosphorous levels. There is clear agreement among all manufacturers that phosphorus is a poison that reduces catalyst efficiency. The only difference is over the level of phosphorus in engine oil that can reasonably be tolerated. Some Japanese manufacturers have clearly decided that lower phosphorous levels with a higher alkaline metals content is the best approach to minimize the formation of phosphorous deposits on catalysts. In general, without being specific as to the level, SAE has supported this position. The introduction of a more stringent antiwear test for engine oils has reversed the trend in declining phosphorous levels in recent years and may in fact lead to a short-term increase. Conversations with engine oil additive manufacturers indicate that phosphorous levels of .10% wt. can be achieved without significant cost increases. Several papers in the literature have suggested that it is possible to achieve lower levels and there is the example of the lower oil specifications put forward by several Japanese manufacturers. With this background, despite specific data from manufacturers on the effects of alternative phosphorous levels, it may be prudent for ARB to pursue a rulemaking that sets an upper phosphorous limit of .10% wt. in engine oils. The long-term effects of extended exposure to phosphorus, while it has been minimized, is bound to contribute to the long-term deterioration of catalyst performance for well-maintained vehicles. Because of the need to achieve attainment of NAAQS for ozone and CO, the elimination of all long-term sources of catalyst deterioration would be a goal worth pursuing.

1.3 Overall Deterioration

Very little data are available on the stability of "engine out" emission levels on vehicles in customer service. Surveillance testing routinely involves only "tailpipe" emission measurements. It is therefore difficult to discern trends in catalyst deterioration by comparing the performance of in-use and certification vehicles unless it is assumed that there is no increase in engine out emission levels over the first 50,000 miles of operation. Because most late-model vehicles have closed loop systems and oxygen sensors are sensitive to chemical and thermal degradation, this assumption cannot be supported. Additional concerns about the effect of ignition and injection system problems also make it difficult to support this assumption. Despite the inability to distinguish between the contributions of catalyst deterioration and engine out emission increases to deterioration, the computed differences between certification and non-tampered in-use vehicles emissions are useful.

In reviewing these results, it is important to remember that MPFI systems with single-bed catalysts are projected to be the predominant technology used on future automobiles. The role of rhodium in the performance of these systems is critical not only to NOx control but also to the control of HC and CO. With this background the following conclusions can be drawn:

- From the perspective of percentage and absolute grams per mile increases, CO emissions exhibit the highest level of deterioration. Despite the high levels of deterioration, several of the technologies have in-use emission levels either below or near their certification standards.

- From the perspective of in-use compliance with the certification standards, the highest level of deterioration is seen in HC emissions. Based on available surveillance data, every one of the technology categories has in-use 50,000 mile levels above the .41 gm/mi standard.

- The lowest level of deterioration of all of the pollutants occurs for NOx emissions; the occurrence of emission levels above the certification standards is negligible. The highest deterioration levels were recorded by late-model, single-bed MPFI systems, indicating possible thermal degradation of rhodium.

- The ability of in-use vehicles to approach certification standards despite high levels of deterioration, particularly for CO, results from the fact that manufacturers purposely design vehicles to account for differences between certification and in-use driving conditions. A "cushion" is required during certification because the program does not subject vehicles to test conditions that are representative of in-use driving experience.

- In general, the deterioration levels of 81+ MPFI systems are not substantially different from those of other technologies. An analysis of their contribution to the emissions inventory in the year 2000, when they are projected to be the dominant technology, indicates that deterioration will be responsible for over 70 percent of the HC and CO, and 50 percent of the NOx automobile emissions inventory. This estimate is based on the results of a BURDEN run that includes the benefits of I/M.

- Improvements to the certification program could be developed to reduce the contribution of deterioration to the emissions inventory.

1.4 Recommendations

Based on the evaluation performed, the authors suggest that ARB consider taking the following actions:

1. To improve the understanding of factors contributing to differences between emissions during certification testing and emissions in customer service...

   - ARB should require manufacturers to supply engine out emissions data at the completion of all 4,000 mile and 50,000 mile tests;
   - ARB should obtain more engine out emissions data on vehicles selected for surveillance testing.

2. To improve the representativeness of the certification durability test, ARB should obtain more catalyst temperature data on a representative sample of vehicles undergoing certification durability testing and operating in typical customer service. (Fleet vehicles owned by the state provide one potential source of test vehicles for obtaining in-use data.)

3. To minimize the fuel-related deterioration of emissions in customer service, ARB should consider a more stringent standard for the lead content of unleaded gasoline. (ARB should also pursue the recommendation of an earlier study to establish a minimum standard for deposit control additives.)

4. To minimize the lubricating oil-related deterioration of catalysts, ARB should limit the phosphorous content of oil to 0.10% by weight and specify a minimum ratio of alkaline metal to phosphorus.

2.0 INTRODUCTION

2.1 Background

Failure to attain the National Ambient Air Quality Standards (NAAQS) for ozone and carbon monoxide (CO) in many areas of the state has forced the ARB to identify areas of additional emissions reductions that can be used to reduce the size of the current inventory and offset future levels of growth. Automotive emissions are responsible for a major portion of the HC emitted and an even larger portion of the CO produced in California. Automotive emissions control strategies have traditionally focused on two areas: increasingly stringent standards that reduce the emission levels emitted by new vehicles; and an I/M program designed to identify the vehicles with excessive emissions that result from tampering, emission control system failures, and the lack of proper maintenance.

The increasing stringency of new vehicle emissions standards has significantly reduced the levels emitted by vehicles tested in certification programs. The goal of the I/M program is to produce an in-use vehicle fleet with emission levels comparable to those achieved in certification. The achievement of this goal, however, depends on the extent to which there are factors other than tampering, component failure, and the lack of proper maintenance that contribute to excess emissions.

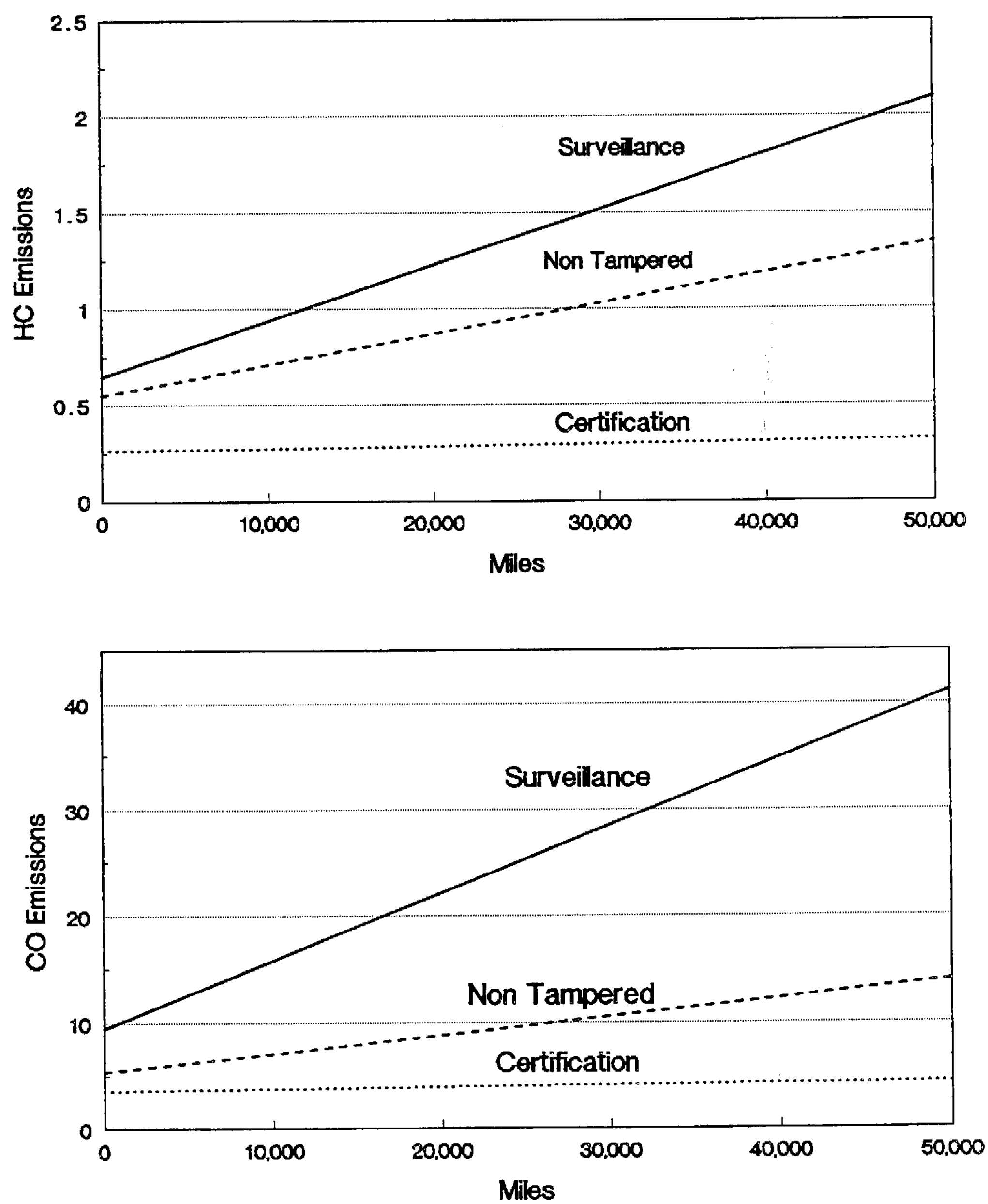
As shown in Figure 2-1, there can be substantial differences between the emissions produced by certification vehicles and those operated under in-use conditions. The figure is based on certification results and data used in the development of emission factors for the I/M model. It shows that the difference can be quite substantial even in cases where no tampering is involved.

Some of the difference between in-use and certification emission levels has been clearly attributed to tampering and the lack of proper maintenance. However, attempts to resolve <u>all</u> of the difference between certification and in-use emission levels have been limited.

As a rule, certification vehicles have extremely low levels of deterioration. "Deterioration factors" of 1.0, that is no deterioration, are not at all uncommon for certification vehicles. Vehicles that participate in the surveillance program and show no evidence of tampering exhibit substantially higher levels of deterioration. Many causes are possible, but all are expected to relate to maintenance and operational differences between the certification program and in-use vehicle experience. These differences have two effects on emissions production: increased engine out emission levels; and decreased catalyst efficiency. The purpose of this study was to identify those factors responsible for the differences in catalyst efficiency.

Figure 2-1

Comparison of Emission Factors for 1977-1979 Throttle-Body and Carburetted Three Way Catalyst Automobiles



2.2 Factors Affecting Catalyst Efficiency*

A catalyst is a substance that promotes a chemical reaction without undergoing any permanent chemical change itself. It increases the rate at which a thermodynamically feasible reaction approaches equilibrium. The following example outlines the influence of a catalyst on a reaction:

$$2NO + 2CO \underset{k_r}{\overset{k_f}{\rightleftarrows}} N2 + 2CO_2$$

In this case k_f and k_r are the forward and reverse reaction rate velocities. A catalyst for this reaction increases the magnitudes of both k_f and k_r and thereby increases the rate at which the four species undergo mutual reaction in either direction until equilibrium is achieved. The essence of a catalyst is that it reduces the potential energy barrier between reactants and products so that the reaction proceeds at a much faster rate.

In general, catalytic reactions proceed via the following series of discrete steps or processes:

- diffusion of reactants from the gas phase to the vicinity of the catalyst surface;
- adsorption of one or more of the reactants on the catalyst surface;
- reaction of the adsorbed species with the other adsorbed species or with nearby gas phase molecules;
- desorption of the reaction products;
- diffusion of these product molecules from the reaction surface through the fluid boundary layer and into the bulk gas phase.

The first step in a catalytic reaction is the diffusion of reactants from the bulk gas stream to the catalyst surface. Regardless of how fast the gas is flowing past the catalyst surface, the viscous nature of the gas will result in a boundary layer of finite thickness at the catalyst gas interface. Within this boundary layer, mass transfer occurs by molecular rather than turbulent diffusion. Molecular diffusion is a relatively slow process compared to many of the other

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* This discussion is largely taken from "Combustion, The Formation and Emission of Trace Species", John B. Edwards, Adjunct Professor, Department of Chemical Engineering, University of Detroit, Ann Arbor Science Publishers Inc., 1977.

chemical reactions that take place and may therefore be the rate-controlling step in determining the overall conversion that can be achieved with a catalyst. To minimize the effect of diffusion rate constraint, one or more of the reactants must have an affinity for the surface of the catalyst. It is also desirable to arrange the surface with the respect to the flowing bulk gases so that the diffusive flux will be as great as is practically possible.

The second step in the overall catalytic mechanism is adsorption. One or more of the reactants in a reaction must be adsorbed by a surface for catalysis to occur. When a species is adsorbed it is in effect concentrated at that surface. The adsorption of a molecule on a surface may be physical or chemical. In the case of physical adsorption the forces that bind a molecule to a surface include permanent dipoles, induced dipoles, quadrapole attractions and the well-known VanderWall's forces. With these forces it is possible for many layers of adsorbed molecules to build up and concentrate the adsorbate.

From the perspective of catalysis, chemisorption is a more important process than physical adsorption. When chemisorption occurs a rearrangement of electrons occurs, producing actual chemical bonds between adsorben and adsorbate. Chemisorption is therefore limited to a single layer of adsorbate molecules, which is held much closer to the surface. Large amounts of energy may be released during chemisorption.

The third step in the overall catalytic mechanism is the chemical reaction that occurs on the surface where the reactants have been adsorbed. The catalyst functions by providing an alternative path for the reaction with a lower energy barrier. The alternative path may produce an intermediate that is quite different from intermediate(s) formed along reaction paths corresponding to high temperature combustion. For example, since a catalytic reaction occurs at a lower temperature, the reaction intermediates that occur along the path may not even be thermally stable at the conditions required at flame reaction of the same species. Therefore, since the reaction mechanism is different and the intermediate species are different, the product distribution obtained from the catalytic reaction of a given set of reactants may differ from the product distribution which is formed when the same reactants undergo flame reaction at much higher temperatures. It further follows that since the other steps in the overall catalytic reaction mechanism, such as adsorption and desorption, are temperature-dependent, the product distribution obtained from the catalytic reaction of a given set of reactants may vary with temperature.

The final two steps in the overall catalytic mechanism are desorption and the diffusion of product molecules from the catalytic surface into bulk gas. The product molecule(s) must not have so high an affinity for the surface that they are tenaciously held and block the available sites. If this occurs the catalyst is said to be product poisoned.

Instead products must readily diffuse out of the pores and away from the surface.

In summary, the overall catalyst reaction rate depends on the rates of the five independent steps outlined above. Usually one of the steps will be slower than the rest and will control the overall rate of the reaction. The factors that govern the slower reaction rate may be related to either chemical kinetics or mass transfer rate. In the case of chemical kinetics, the rate of the reaction will be governed by temperature and reactant concentration. In the case of mass transfer the rate of the reaction can be influenced by the nature of the catalyst surface, the size of its pores (if any) and its geometric arrangement with respect to gas flow. The remainder of this report will address the differential effects that high temperature operation and chemical poisoning have on the factors that govern the rate at which catalytic reactions occur.

2.3 Technical Approach

The purpose of this study was to identify those factors responsible for the differences in catalyst efficiency. It is an accepted fact that there are no physical differences between the catalysts used on certification vehicles and the catalysts used on production vehicles. The factors known to affect catalyst performance suggest that greater in-use deterioration is the result of impurities or contaminants (poisons) contained in gasoline and lubricating oil used in customer service versus those employed in the certification program, and the possibility that catalysts are subjected to greater thermal stress in customer service than they experience during certification testing. The approach used for the analysis was to conduct an extensive literature review of these factors that are known to affect catalyst durability. This effort was divided into two separate areas: thermal degradation and chemical poisoning. Contacts were established with automobile and catalyst manufacturers to review the results of that survey and to collect additional data and information. Separate contacts were established with refiners, oil additive manufacturers and professional societies to collect additional information.
The discussions with these researchers provided valuable insights into the mechanisms of deterioration. Some of the people contacted preferred that the conversations be "off the record" to minimize conflicts with supplier relations or company policy. In the body of the text, specific references to these conversations are not provided, instead a general reference to "conversations with industry sources" is noted. A summary of the manufacturers contacted is presented below:

Ford Motor Company
General Motors Corporation
Chevron Research
Chevron Chemical
Lubrizol
Johnson-Matthey, Inc.

W. R. Grace Co.
Engelhard Corporation

Contacts were also established with analytical and certification departments of EPA and ARB to collect data and insight relevant to the analysis.

Following the literature review and contacts with specialists in the industry, the analysis was generally divided into two areas: identification of the mechanisms that govern catalyst deterioration and the threshold at which they occur (e.g., impact of specific temperature levels on noble metal sintering, etc.); and determination of the range of conditions experienced by certification and in-use catalysts (e.g., distribution of temperatures experienced by catalysts under certification and in-use operation, etc.). The combination of information on mechanisms and operating conditions was used to evaluate the extent of their impact on differences in catalyst efficiency.

A separate analysis was conducted to quantify the difference in emissions produced by certification and in-use vehicles. Surveillance and certification program data were used to produce these estimates. Separate estimates of deterioration were developed for each of the technology categories employed in the development of the I/M model.

Unfortunately, the surveillance program does not include data on the performance of vehicles later than the 1983 model year. Many of the emission control systems and catalysts contained in the data set are not representative of those that are and will be employed on future vehicles. Therefore, the analysis focused on the performance of three-way catalyst systems.

2.4 Organization

Section 3 provides an extensive discussion of the mechanisms governing the effects of high temperature operation on three-way catalyst activity. An analysis of the range of temperatures experienced in normal operation and in the certification program is then presented. A summary integrating the results of the two analyses follows.

Section 4 provides a discussion of the effects of fuel and oil contaminants on catalyst performance. The information on fuel contaminants is derived from the Task 5 report. The analysis of the oil contaminants, primarily phosphorus, first addresses mechanisms and then the distribution of phosphorus contained in in-use oils. A summary section contrasts the fuel and oil contaminant effects on catalyst durability.

Section 5 presents estimates of deterioration by pollutant and technology control category. An overall estimate of the impact of deterioration on the emissions inventory in the year 2000 is presented.

3.0 THERMAL DETERIORATION

A large body of literature has been developed over the past ten years as researchers have worked to understand the mechanisms governing the effects of high temperature operation on three-way catalyst activity. Increased demands for catalyst formulations that can survive under high speed and high load conditions (e.g., medium and heavy-duty truck use, European driving, etc.) have focused attention on the need for improved thermal stability. Temperatures encountered under these conditions can alter both the substrate and washcoat and result in major losses of catalyst activity. High temperature transient spikes can also occur under "normal" operating conditions and subject catalysts to temperatures in excess of 2000°F. The need for increasing thermal durability has led to a continual series of improvements in catalyst formulations that allow the active metals to survive and function at ever increasing temperatures. Commensurate with the catalyst improvements, there have been steady trends towards the use of fuel metering and emission control system designs that have reduced the frequency of damaging high temperature excursions.

To determine the sensitivity of in-use catalyst formulations to thermal degradation it is necessary to understand the mechanisms that govern deterioration and know the temperature levels that vehicles experience under in-use conditions.

3.1 Thermal Deterioration Mechanisms

As catalyst technology has improved, formulations have become more complex as new materials have been added to stabilize existing materials and promote pollutant conversion under adverse conditions (oxidizing or reducing). Current three-way catalyst formulations are generally composed of the following elements:

- A honeycomb substrate generally made of cordierite, a relatively strong, moderately porous ceramic material ($2Mg2Al_2O_35SiO_2$);

- A very high surface area refractory material added as a coating ("washcoat") to the substrate to increase the specific surface area; γ-alumina (Al_2O_3) is frequently used.

- Base metal promoters added to the washcoat to improve CO and NOx performance around stoichiometric air/fuel ratio. Ceria and nickel have been shown to improve thermal stability of alumina, increase O_2 storage capacity of three-way catalysts, and stablize noble metals in a finely dispersed state.

- Noble metals catalysts, platinum (Pt) or palladium (Pd) to oxidize HC and CO, and rhodium (Rh) to reduce NOx to nitrogen, are deposited on the washcoat surface in extremely low concentrations (e.g., 0.2 wt% Pt).

The above description applies to "monolithic" catalysts with "honeycomb" substrates. "Pelletized" catalysts (no longer as popular) are also used on some vehicles. The individual pellets (nominally 1/8" in diameter) are spheres or cylinders made of the same alumina material that is coated onto a monolithic catalyst.

High temperature excursions and sustained high-temperature operation can influence the structure and interactions of all of the above components, which in turn affect catalyst activity and conversion efficiency. Before reviewing the actual effects of high temperature operation on catalyst efficiency, the following background information is presented.

The three principal catalysts used in automotve catalytic converters have different characteristics:

- Pt has good chemical poison resistance, but is sensitive to high temperature deactivation resulting from a loss of surface area when "sintering" occurs.

- Pd has good thermal stability, but is sensitive to chemical poisoning.

- Rh is very sensitive to lean high temperature aging.

There are three different types of temperature damage that can occur:

- Sintering of noble metals is a concern because, if the temperature is high enough, migration of the finely dispersed noble metal particles into clusters occurs and the surface area of the catalytic material (sometimes referred to as the number of "active sites") is reduced. This loss of surface area increases the time required to achieve "light-off" (defined as the achievement of a 50-percent conversion efficiency). The increase in light-off time increases the volume of pollutants that passes through the catalyst untreated. Since the bulk of HC and CO in most cycles is produced under cold start conditions, the delay in light-off time has a significant effect on overall conversion efficiency. Surface area loss also reduces the maximum efficiency of a warmed-up catalyst.

- The substrate surface is covered with a thin alumina coating (washcoat) to increase the surface area on which the noble metals are distributed. At high temperatures the alumina can flow and undergo phase transitions that cause a shift from high surface area γ-alumina to lower surface area α-alumina. The effect of the lower surface area is to decrease the exposure of exhaust gas to noble metal particles dispersed on the surface. The effects of this surface area loss are the same as described above. Rh interactions with alumina are also influenced by temperature. At higher temperatures Rh diffuses into the subsurface and loses surface area.

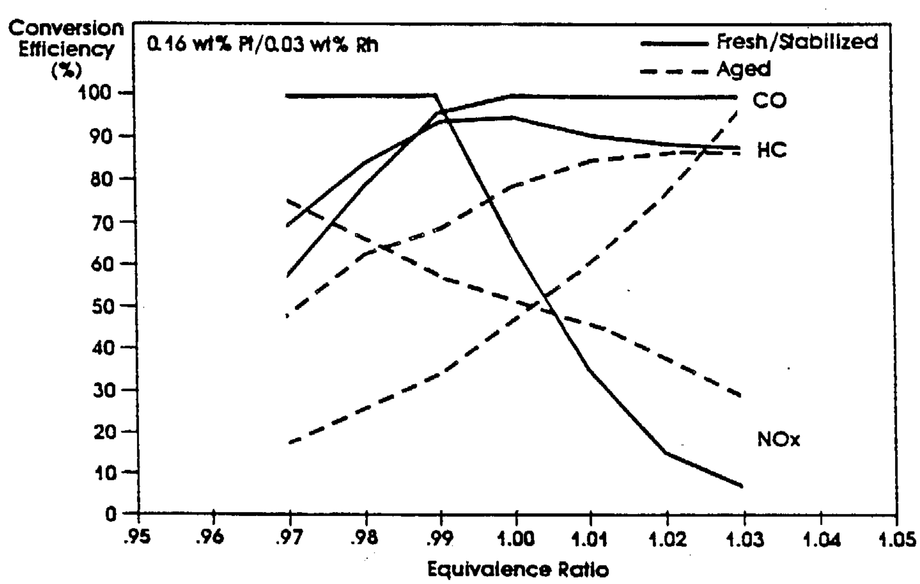
- At sufficiently high temperatures, the cordierite substrate itself can actually sag or melt. This can cause the pores of the substrate to close up, thereby blocking the flow of exhaust gas into the pores and reducing the surface area of the washcoat that is in contact with the exhaust.

High temperature excursions do not cause step function changes in catalyst activity. The effect is complex and dependent on the material, exhaust gas composition, and aging time.

The effects of sustained high temperature operation on catalyst performance are best described in Figure 3-1 which shows the results of a Johnson Matthey[1] analysis of a fresh and a thermally deactivated catalyst. The deactivated catalyst was aged for "50 hours on an engine dynamometer operating at 800°C (1472°F) in a stoichiometric exhaust with lean (3% excess O_2) 1050°C (1922°F) spikes every 1.3 minutes." The figure shows that thermal deactivation varies by pollutant and equivalence ratio. There is a large decline in CO conversion efficiency, particularly at and rich of stoichiometry. The

Figure 3-1

The Effect of Thermal Deterioration on the Performance of a Conventional Ni/Ce Promoted Pt/Rh Three-Way Catalyst



Source: B.J. Cooper and T.J. Truex, SAE Paper #850128, 1985 decline in HC conversion efficiency is much less significant and confined largely to rich conditions. NOx performance is suppressed under rich conditions but is apparently enhanced under lean conditions, a phenomenon that has not been explained in the literature to date. Under very lean operating conditions, CO and HC conversion efficiencies exhibit minimal reductions.

The authors reported that "CO conversion in the stoichiometric and rich region is very dependent on the number of active sites, i.e., kinetically limited, and therefore is susceptible to thermal deactivation. Lean CO and HC conversion is not dependent on site availability, i.e., is diffusion influenced or controlled, and therefore is relatively unaffected by thermal deactivation." The overall finding of the study was that thermal deactivation leads to a large loss in conversion efficiency at and rich of stoichiometry for CO and for NOx. The mechanisms governing the loss of NOx performance are much more complex as they include interactions between Rh and alumina and Rh sintering.

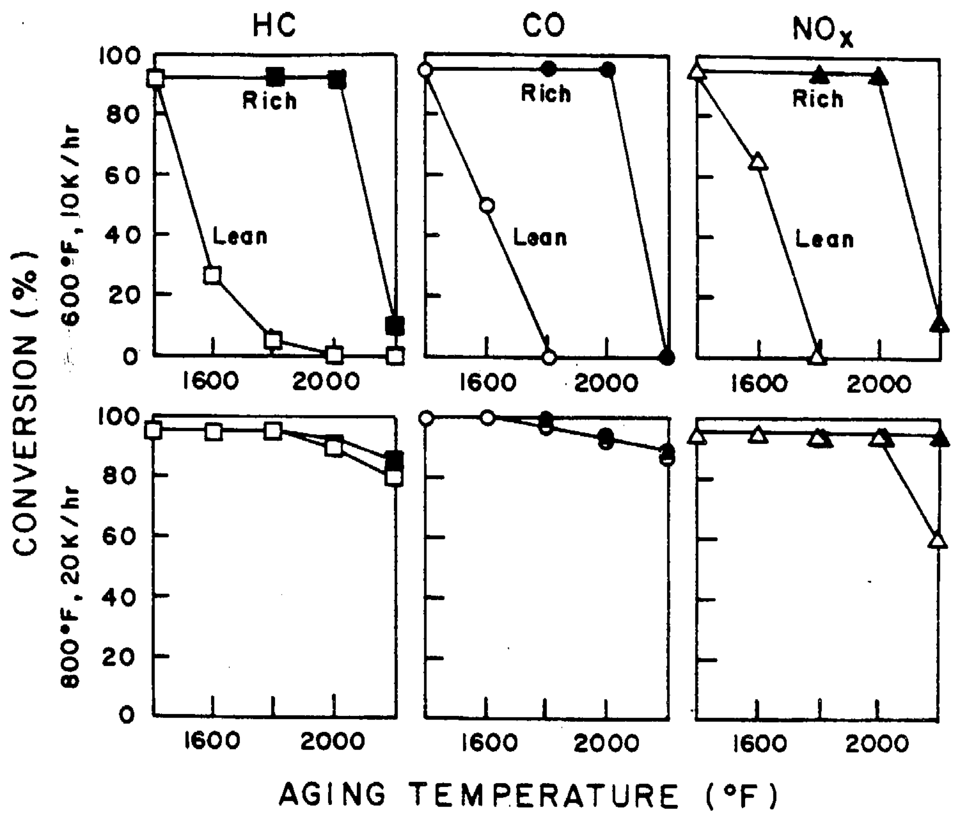
Many studies have determined that thermal deactivation is dependent on the duration, temperature and air-fuel ratio experienced during the high temperature exposure. These conditions affect the rate of loss of active metal surface area which in turn determines the performance effects outlined in Figure 3-1. Ford[2] conducted an extensive investigation into the effects of high temperature conditions on conversion efficiency. Catalysts were aged using the emission durability cycle, which had a maximum catalyst temperature of 1,100°F. The catalysts were exposed to brief periods of higher temperatures at a rate of 1 minute per hour in an effort to simulate the conditions that an in-use vehicle might experience. The catalysts were exposed to temperatures of 1,800, 2,000 and 2,200°F at rich air fuel ratios and 1,400, 1,600, 1,800, 2,000 and 2,200 °F at lean air fuel ratios. The catalysts were aged for a total of 60 hours or 60 minutes of high temperature operation. Figure 3-2 displays the results of three-way conversions at stoichiometry at temperatures of 600 and 800°F for each pollutant separately.

It is clear that catalysts aged under lean conditions with high temperature exposure show the greatest loss in conversion efficiency. The conversion efficiencies measured after exposure to 1,600°F operation for HC, CO and NOx were 27, 50 and 65 percent, respectively, for exhaust gas temperatures of 600°F. This compares to 90+ percent efficiency after 1,400°F aging. Similar measurements at 800°F catalyst inlet temperature show that, except for exposure to temperatures above 2,000°F, efficiency losses are minimal.

Additional measurements of catalyst efficiency at 600 and 800°F as a function of aging time and air fuel ratios were also recorded. They showed that almost all catalyst activity was lost, as measured at 600°F, when exposed to periodic high temperatures above 1,800°F in the presence of lean air fuel ratios for 20 minutes. Similar levels of deactivation were noted within 20 minutes when catalysts were exposed to 2,200°F in the presence of rich air fuel ratios.

Figure 3-2

Three-Way Catalyst Conversions at Stoichiometry as Measured at 600 and 800° F Inlet Temperature as a Function of a Catalyst Aging Temperature and Air-Fuel Ratio



Source: R.H. Hammerle and C.H. Wu, SAE Paper #840549, 1984.

To explain the differences in catalyst efficiency noted between 600 and 800°F for varying fuel ratios, the authors noted that reactions proceed at different speeds, and that it is the speed of the reaction combined with the available surface area that determines when reactions begin to deteriorate due to high temperature exposure. They defined three relative categories of speed at which reactions take place at 800°F:

- the oxidation of HC and CO under lean conditions is the base;
- the oxidation of CO and HC under rich conditions is roughly an order of magnitude slower than the base conversion;
- the reduction in NOx is approximately an order of magnitude slower than CO oxidation under rich conditions.

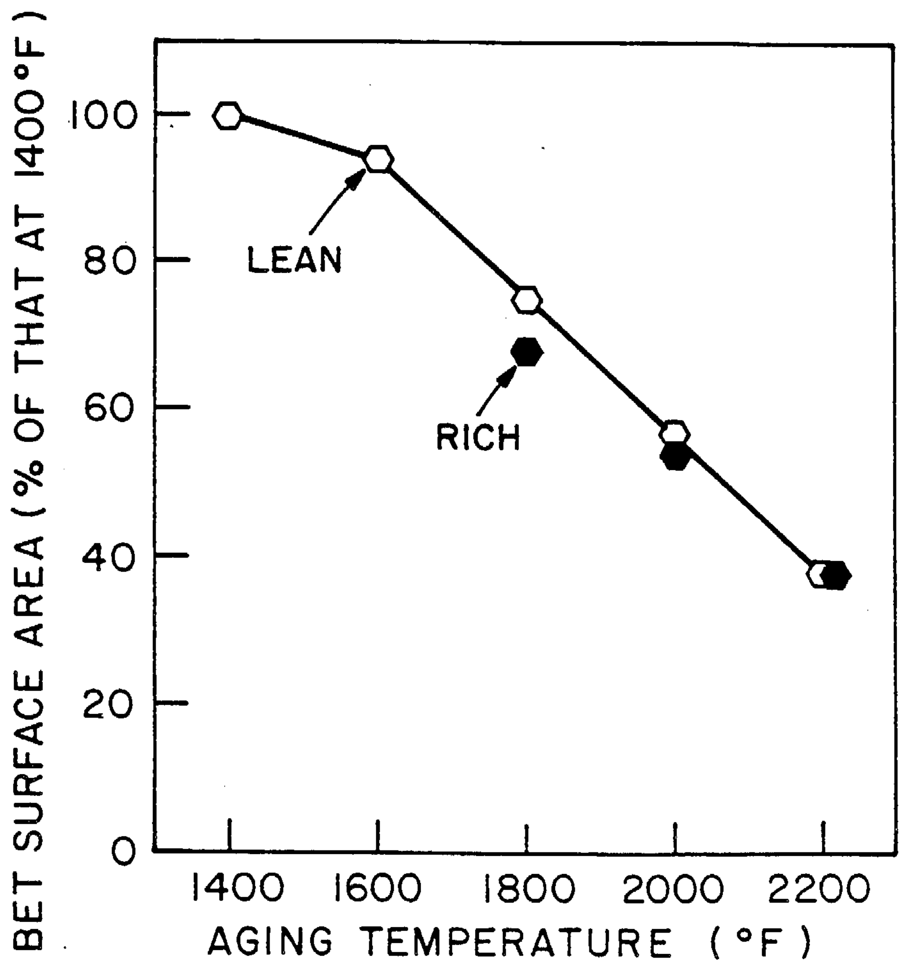
As discussed in the introduction, the speed at which the above reactions occur is governed by 5 separate processes. The influence of temperature is not the only factor that governs the rate at which these processes occur. Many other factors influence the overall reaction rate (e.g., available surface area, surface geometry, diffusion rate, etc.). The authors, however, felt that "as the noble metal surface area in a catalyst decreases from the fresh state, the performance of the catalyst as measured at 600°F and 800°F may not be affected immediately because the TWC retains sufficient surface area to bring the reactions involved to the limit of the diffusion transfer of the reactants to the active metal. This is the case for catalysts heated to 1400°F with a lean air-fuel ratio and to 1800°F with a rich air fuel ratio since their performance as measured at 600 and 800°F barely changed compared to the fresh state. With higher aging temperatures - 1600°F under lean conditions and 2000°F under rich conditions and with the resultant loss of surface area, the rate of the slower reactions such as NOx reduction, and HC and CO conversions in the oxygen deficient atmospheres" is diminished while the faster reactions remain unaffected. They also noted that "with higher aging temperatures - 1800°F under lean conditions and 2200°F under rich conditions - and with even greater surface area loss, the faster reactions such as HC and CO oxidation are also affected by the loss of surface area, especially as measured at 600°F."

The light-off performance of catalysts decreases as exposure to aging temperature increases. Several studies have noted a marked reduction in the surface area as temperature increases. The loss in surface area translates into increased time and inlet temperature requirements needed to achieve light-off. Figure 3-3 displays the results of BET* surface measurements taken in the Ford analyses. It compares the change in surface area of the washcoat as a function of aging temperature and air fuel ratio. There is essentially no difference in

* named from Branaur, Emmett and Teller - individuals in the 1930's who developed a method to predict the surface area of solids.

Figure 3-3

BET Surface Area of Three-Way Catalyst Washcoat as a Function of Catalyst Aging Temperature and Air-Fuel Ratio



Source: R.H. Hammerle and C.H. Wu, SAE Paper #840549, 1984 the surface area loss between rich and lean operating conditions. The loss in surface area is roughly the same and exhibits a steady downward trend with increasing temperature.

The figure shows that significant surface area losses, greater than 60 percent, are possible after exposure to 2,200°F temperature for 60 minutes. That finding, however, provides no insight into the differential catalyst performance noted at 600 and 800°F. It suggests, however, that the impact of the high temperature aging has a differential effect on the active metals employed in the catalyst formulation. A review of the literature shows that higher temperatures and exhaust stoichiometry have separate effects on three primary catalyst materials:

- loss of alumina surface area,
- accelerated growth in Pt and CeO_2 crystals, and
- Rh sintering and its interactions with alumina.

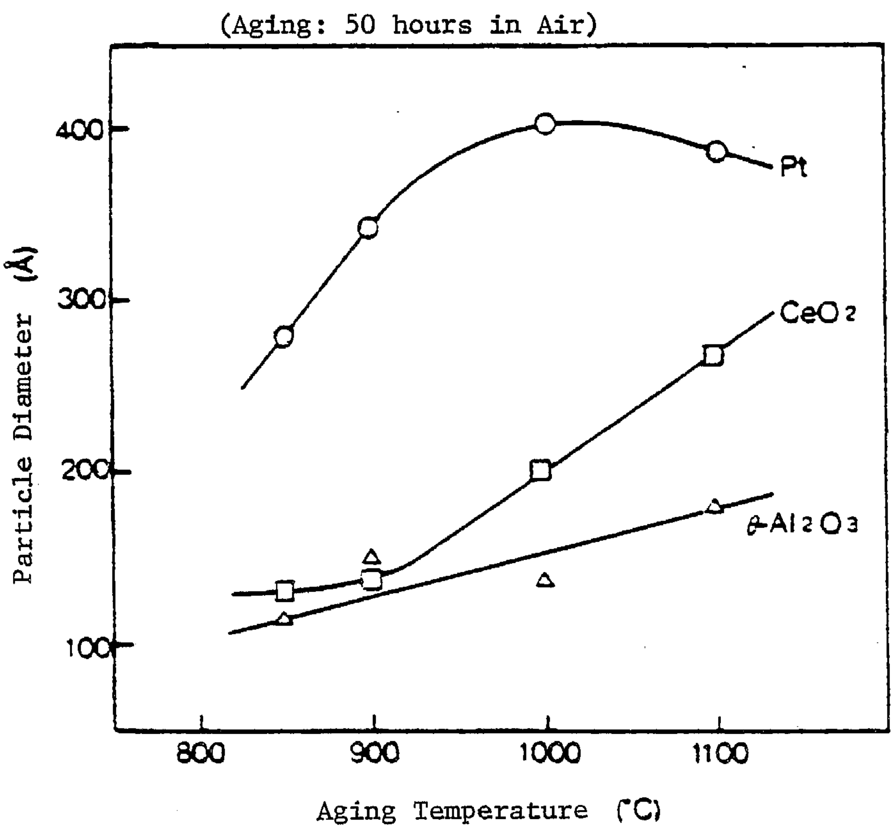
Researchers at Mazda[3] also observed that catalysts aged under lean conditions experienced elevated levels of deterioration relative to catalysts aged under rich conditions. Their studies indicate that even a small amount of oxygen in the aging atmosphere can lead to sharp drops in catalyst activity, and that the extent of deactivation is independent of the oxygen concentration. They also found that at temperatures above 900°C (1652°F) the alumina undergoes a sharp loss in surface area regardless of the exhaust stoichiometry. The primary cause of surface area loss is shrinkage of micro-pores of 100A or less. The loss of the active sites contained in micro-pores of 100A or less has a large effect on catalyst activity.

A separate analysis of the effect of lean high temperature operating conditions was conducted to determine the effect of temperature on particle size growth for Pt, CeO_2 and alumina. The results are displayed in Figure 3-4. It shows that Pt crystal growth continues accelerating up to 1,000°C (1,832°F) and that CeO_2 crystal growth undergoes a sharp rise at temperatures above 900°C (1,652°F). Separate measurements indicated that γ-alumina undergoes a phase transition to lower surface area α-alumina at about 900°C. That conversion was felt to be responsible for the loss of micro-pore volume discussed above.

Additional measurements showed that the crystal growth observed under lean operating conditions for Pt and CeO_2 was nonexistent under rich conditions. The aging atmosphere was found to have little influence on alumina crystal growth. The severe deactivation that catalysts experience under lean operating conditions is thought to be "based on the reason that Pt tends to easily generate volatile PtO_2 in the presence of oxygen, so triggering particle migration via the gaseous phase or along the substrate surface for eventual agglomeration." A similar mechanism is thought to govern the change in CeO_2. Thus the severe degradation noted for catalysts operating under high

Figure 3-4

Effect of Aging Temperature on Particle Size: Aluminum, Platinum and Cerium Oxide



Source: K. Ihara, et al., SAE Paper #871192, 1987 temperature lean conditions is thought to be due to the combined effects of a decrease in the number of active points and a drop in the oxygen storage performance. The lack of Pt and CeO_2 crystal growth under rich, high-temperature conditions is thought to be the primary cause for the difference in catalyst performance noted relative to lean aging.

Many studies have noted the extreme sensitivity of Rh to lean high temperature operating conditions. Rh is critical to single-bed three-way catalyst performance, because it contributes not only to NOx reductions but also to CO and HC oxidation as well. The loss of Rh contributions to these reactions diminishes the overall performance of a single-bed system for all pollutants.

Three primary Rh interactions have been identified as significantly diminishing Rh's function in catalyzing CO, HC and NOx conversion:

- interactions between high surface area γ-alumina substrate and Rh,

- interactions between rare earth oxides used in the alumina support matrix and Rh, and

- Rh sintering.

Several studies have shown that at temperatures under 600°C (1,112°F) rhodium oxide (Rh_2O_3) has weak interactions with γ-alumina. At temperatures above 600°C in an oxidizing atmosphere, Rh_2O_3 interacts strongly with γ-alumina and diffuses into the subsurface region. Thus, at higher temperatures Rh loses surface area. These interactions have been well known for a long time and a large body of research has developed in an effort to allow Rh to "live" in higher temperature environments. Research into Rh usage is also economically motivated by the need to bring catalyst Rh levels which generally have Pt to Rh ratio of 5 to 1, closer to the mine production ratio of 19 to 1. Any technology that can be developed to improve the performance of Rh and reduce the amount required to achieve certification would have substantial economic benefits.

In 1986, Engelhard[4] conducted an analysis of the effects of thermal aging on conversion efficiency for a standard three-way single-bed formulation (A) and one that has been designed to segregate Rh from the rare earth supports (B). The B formulation was designed to minimize the two lean high temperature interactions known to cause Rh deactivation:

- α-alumina interactions, and

- rare earth interactions.

To accomplish that goal, catalysts were designed with optimal Rh particle size dispersion on the alumina support to minimize interaction while maintaining reasonably high activity levels. The Rh precious metal fraction was also segregated from the rare earth oxide component to avoid Rh interactions with it. The catalysts were then operated on an aging cycle with an operating temperature of 590°C for 44 minutes followed by 4 minute excursions of lean high temperatures of 750°C (1,382°F) for a total of 300 hours (thought to be representative of 50,000 miles of vehicle aging). The relatively low high-temperature excursions employed in the test were designed to evaluate the impact of thermal stress on Rh only. Higher temperatures would affect the performance of other materials and not provide insight into the nature of Rh interactions.

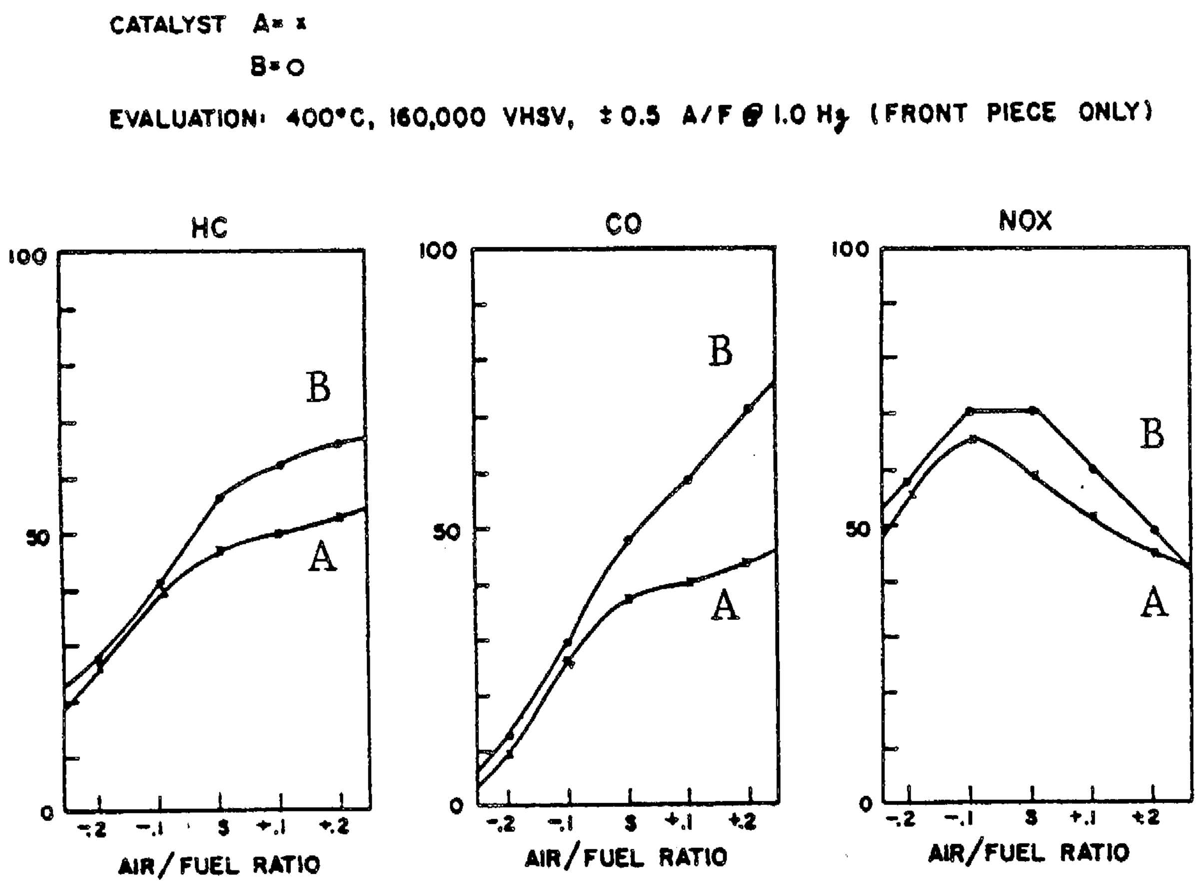
Figure 3-5 is of interest because it shows the relative impact of Rh support interactions on conversion efficiency for each pollutant separately. The segregation of Rh is shown to improve the conversion efficiency of all three pollutants at and lean of stoichiometry. This reflects the high activity of Rh under increasingly lean conditions and its contribution to CO control and, to a lesser extent, HC conversion. There is also a significant but smaller improvement in NOx conversion at and rich of stoichiometry reflecting the improved stability of Rh. The improvements displayed in the figure should be qualified because they represent the test results of the "front unit of a dual unit catalyst." Nevertheless, it shows that substantial improvements in Rh durability can be achieved. The low peak efficiency levels displayed for all three pollutants are thought to be the result of the cycle used to simulate 50,000 miles of operation.

Another area of catalyst research has focused on elevating the melting point of ceramic substrates to protect against extreme transient temperature spikes. Cordierite, the most common substrate material, exhibits sensitivity to melting at temperatures above roughly 1,400°C (2,552°F). A recent paper by W. R. Grace[5] shows that this temperature can be increased by 200°C by using stabilized mullite-aluminum titanate. By "retaining heat during decelerations", the higher density of the monolith material was determined not to result in performance penalites due to longer light-off times. Data were also presented on the benefits of a proprietary washcoat that employed ceria and thermally stabilized γ-Al_2O_3 for use in high-temperature service operations. FTP measurements taken after 100 hours of cyclic high temperature aging with lean excursions up to 1,000°C indicated that the improved formulation could allow volume reductions of up to 22 percent with no loss in conversion efficiency. With the same catalyst volume, durability should therefore be improved.

A summary of the threshold temperature and exhaust stoichiometry at which mechanisms govern the deterioration of catalyst efficiency is presented in Table 3-1. It is not exhaustive and ignores many of the Pt-, Pd- and Rh-alloying interactions that are known to occur in the 700-1,100°C temperature range. Instead it focuses on those thermal deterioration mechanisms that recent literature has suggested are primarily responsible for losses in catalyst efficiency. These mechanisms are quite complex and dependent not only on the temperature and exhaust stoichiometry, but the amount of time that the catalyst has been exposed to these conditions. Thus, the mechanisms listed

Figure 3-5

The Effect of Rh Durability on Conversion Efficiency by Pollutant



Source: C.Z. Wan and J.C. Dettling, SAE Paper #860566, 1986 should be considered approximate indicators of the conditions at which deterioration begins to occur.

It is important to note that catalyst technology is not static and that improvements are continually being developed to elevate the threshold temperatures at which the above noted reactions occur. The implementation of catalyst-forcing emission control standards in Europe, combined with the higher thermal demands encountered there in driving, have stimulated a great deal of research into the development of catalyst technologies that can survive under those conditions. Unfortunately, little data are available to quantify the in-use performance of vehicles that are operating in that environment.

TABLE 3-1

Summary of Primary Thermal Deterioration Mechanisms For Single-Bed Three-Way Catalysts

Approximate Temperature (°F)	Deterioration Mechanism	Exhaust Stoichiometry
1,292	Rh-Al_2O_3 Reaction Pt sintering	Lean Lean and Rich
1,382	Rh rare earth oxide interaction	Lean
1,472	Pt crystal growth	Lean
1,652	CeO_2 crystal growth γ-alumina - α-alumina	Lean Rich or Lean
2,552	Cordierite melting	Rich or Lean

Catalyst and automobile manufacturers were contacted to discuss the findings presented below. There was general agreement over the trends noted and the basic thermal deterioration mechanisms identified. There was, however, disagreement over the temperature threshold above which the risk of substantial catalyst degradation occurs. Auto industry sources indicated that temperatures above 1,400°F (760°C) caused substantial damage to Rh, even though the literature suggests that deterioration begins at lower temperatures. Catalyst manufacturers indicated that the threshold for thermal damage was in the range of 1,600-1,800°F (871-982°C) for catalysts in general. (Note that this is significantly higher than the threshold reported in recent technical papers and illustrated in Table 3-1.) They pointed towards the development of catalysts for European vehicles and heavy-duty trucks as proof of their ability to survive in higher temperature environments. Sierra reviewed the literature and found that little data are available to confirm this assertion. Several papers have addressed the development of prototype systems for European operations; however, all have concluded that additional research is necessary to address specific problems.

3.2 Certification versus In-use Temperature Experience

A critical element needed to understand the extent of catalyst deterioration in well-maintained vehicles is the range of temperatures experienced in "normal operation". The information presented in the previous section indicates that lean temperature excursions above roughly 1,400°F, even for short periods of time, can cause significant damage to the catalyst. In light of that information, the emphasis that some manufacturers have placed on catalyst protection strategies that, for example, "dump" air under extended idle conditions, becomes understandable. However, the fact that manufacturers pursue that strategy indicates that vehicles operated under in-use conditions must frequently approach a temperature threshold for catalyst damage.

Sierra conducted an extensive search for measurements of catalyst and feedgas temperatures characterizing both certification and in-use conditions. Contacts were established with catalyst vendors and the Certification Departments of ARB and EPA; a detailed review of the literature was also conducted. Contacts with vehicle manufacturers indicated that they considered the data proprietary. Certification contacts provided essentially no data. Manufacturers are required to submit catalyst temperature data to EPA and ARB under Advisory Circular 17F to demonstrate that "carryover and carry across" of certification data will not result in increased thermal degradation of the catalyst. It was clear from contacts with certification and analytical "shops" within both agencies that these data have not been studied.

Contacts with catalyst vendors indicated that they do not conduct independent data collection exercises to track temperature experience of vehicles in the field; they get their information on in-use temperature experience from manufacturers. Vehicle manufacturers appear to regularly run instrumented vehicles to determine the range of temperatures encountered under certification conditions. Their knowledge of temperature experience from in-use operation is less clear. Neither EPA nor ARB have been very active in collecting this information from the manufacturers or through independent studies.

Fortunately, EPA has conducted two studies[6,7] in recent years that produced temperature data characterizing in-use operation and certification experience of late-model vehicles. A 1986 analysis of aftermarket catalyst durability generated measurements of the inlet and exhaust temperatures that an OEM three-way dual-bed catalyst experienced on several different road routes. Measurements of engine RPM and catalyst inlet and exhaust temperatures were collected every 10 seconds to profile three standard tire-wear test routes.

Route W-4 - is characterized as a "slow wear" route. Its course consists entirely of dual-lane interstate expressways, 15 percent in West Virginia and 85 percent in Maryland.

Route W-10H - is considered by the tire industry as a "medium wear" route. It consists almost entirely of interstate expressways, with a 50/50 split between Maryland and West Virginia. Compared to the slow-wear route, this route's more extensive driving in mountainous terrain adds more turns and grades to the vehicle's duty cycle.

Route M-101 - is a "high wear" route developed to simulate European driving. It includes 250 miles of interstate expressway driving and 250 miles of mountainous driving which include hard turns and grades of up to 20 percent. The driving is split 60/40 between Maryland and West Virginia.

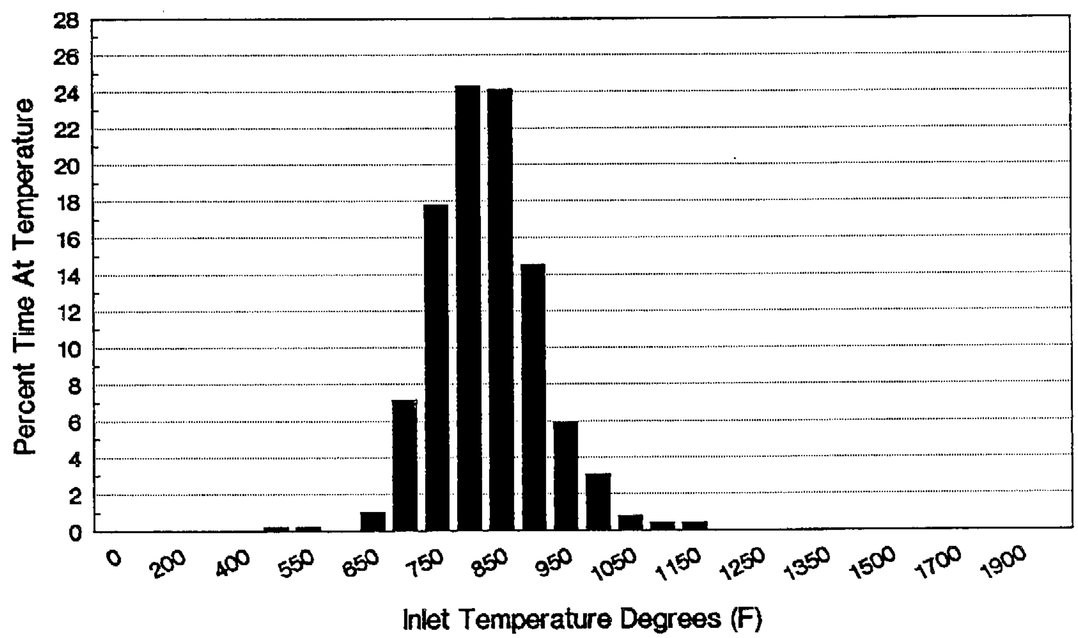
This study also collected similar measurements for the same vehicle operating on the 55 and 70 mph cycles mandated under the durability (AMA) driving cycle. These measurements were conducted on the test track at the Transportation Systems Center in Ohio. Plots of the distributions of catalyst inlet temperatures recorded on the AMA cycles are displayed in Figure 3-6. They show that the maximum temperatures experienced did not exceed 1,150°F under either cycle. The average values were 847 and 820°F for the 55 and 70 mph cycles, respectively. These values agree with the cycling temperatures noted in the literature as representative of temperatures experienced under durability schedules.

The inlet temperatures, measured 1 inch forward of the catalyst inlet for all cycles, are displayed for all of the AMA cycles because they had the highest recorded temperatures. The outlet temperatures, measured 1 inch aft of the catalyst outlet, averaged roughly 50 and 25°F <u>less</u>, respectively, than the inlet temperatures noted for the 55 and 70 mph cycles. These differences may be the result of a catalyst protection scheme to minimize catalyst damage under wide open throttle (WOT) conditions. They may also be an artifact of a 10-second measurement cycle.

Figure 3-7 compares the distribution of the inlet temperatures recorded under the three tire wear routes. There are no significant differences among the temperatures recorded for each of the three routes. On two of the three routes, the maximum temperature was also

FIGURE 3-6

Time and Temperature Distribution Experienced by an OEM Catalyst Under The AMA Cycle at 55 mph



Time and Temperature Distribution Experienced by an OEM Catalyst Under The AMA Cycle at 70 mph

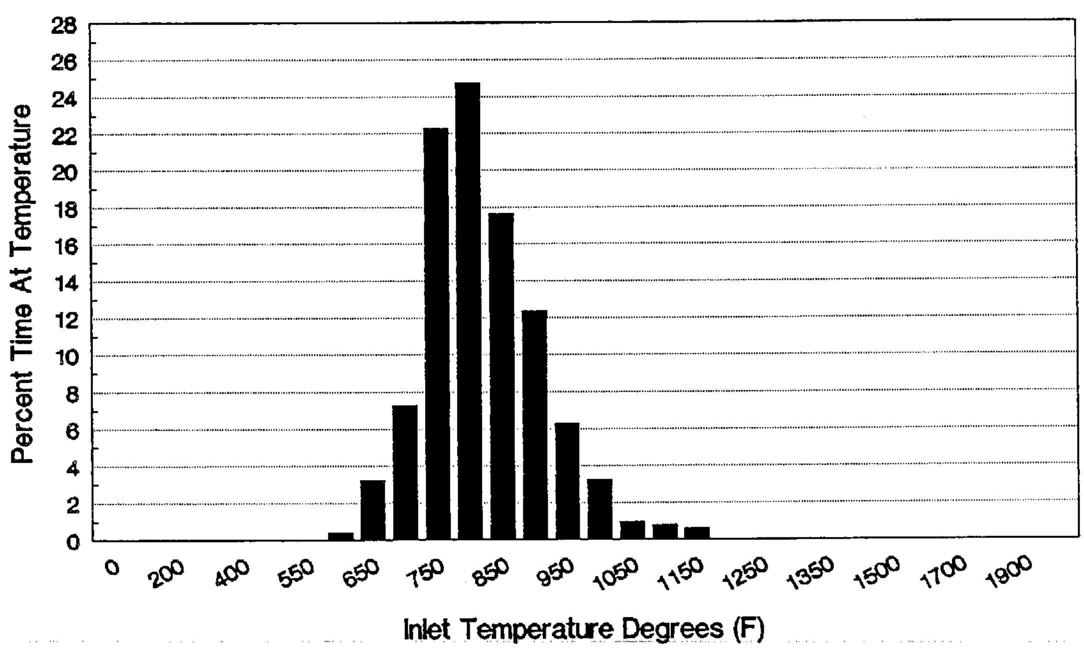
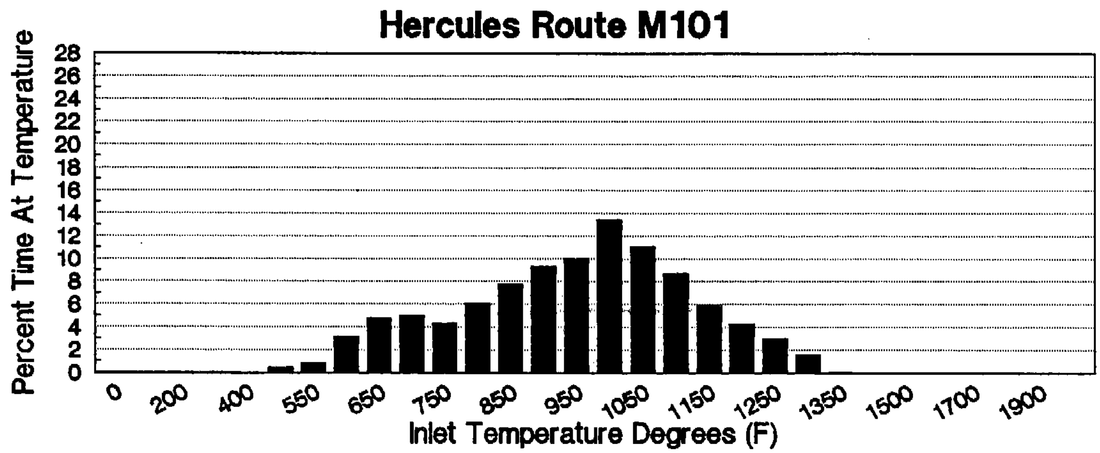
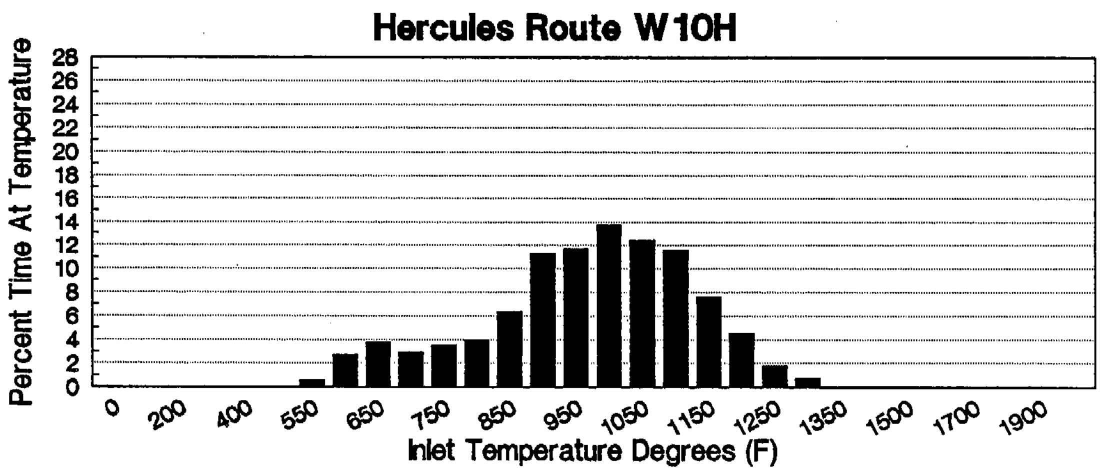
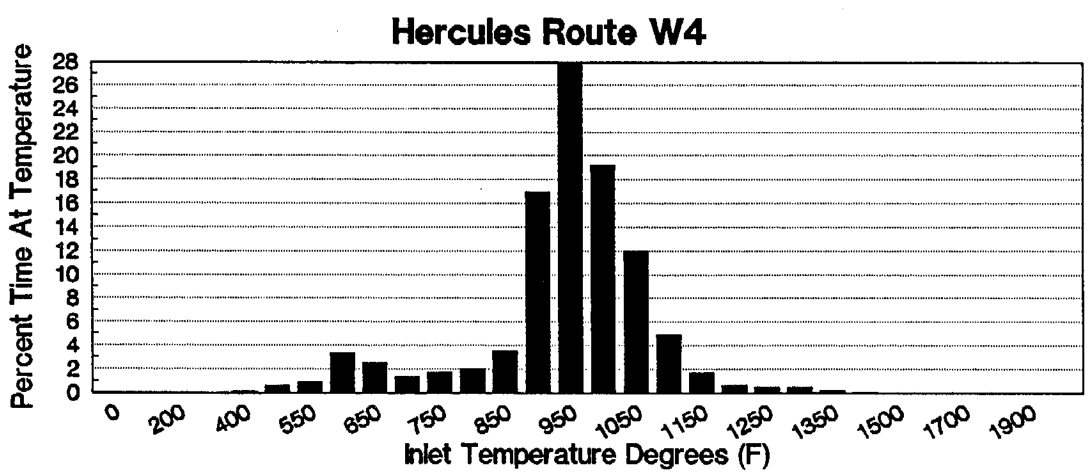


FIGURE 3-7

Time and Temperature Distribution Experienced by an OEM Catalyst Under







recorded at the catalyst inlet. The average values recorded at the inlet and outlet are displayed below:

Average Catalyst Temperature
°F

Route	Inlet	Outlet
W-4	941	939
W-10H	965	1,008
M-101	945	1,004

There is little difference between the inlet temperatures and a slight difference between the outlet values. It is surprising that the most difficult tire wear did not produce the maximum temperature recorded. In fact, the maximum temperature - 1,400°F - was recorded on the slowest wear route. However, there were significant differences between the temperatures recorded on the AMA cycle and those recorded on the road routes.

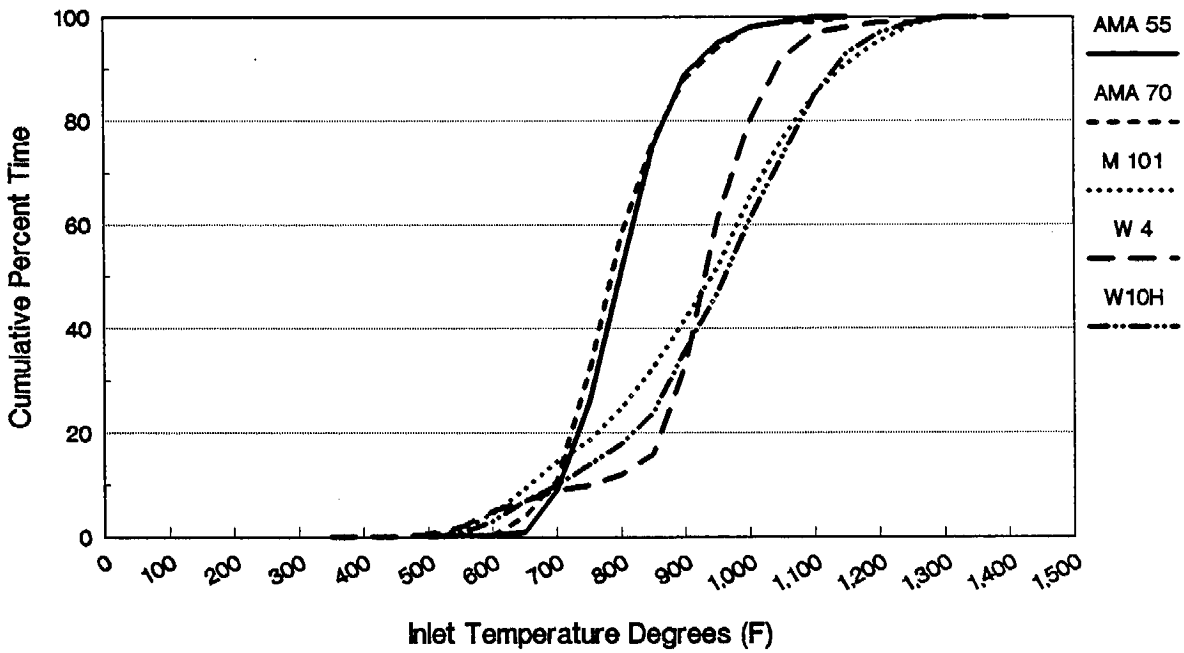
Figure 3-8 provides a comparison of the cumulative time distribution of temperatures that were recorded on the tire test and AMA cycles. There is a noticeable difference between the two types of cycles. The AMA cycles do not thermally stress the catalyst relative to any of the in-use tire wear routes. Even the "slow wear" route which consists of interstate expressway driving shows a higher temperature profile than the AMA cycles. <u>This difference appears to indicate that vehicles do not experience representative catalyst temperatures on the AMA cycle.</u> The lack of loading translates into lower exhaust and catalyst temperatures. Thus, durability vehicles are not experiencing the thermal stress that in-use vehicles encounter.

The EPA data also suggest that while there is a substantial difference between the AMA and in-use cycle temperatures, the maximum temperatures recorded on the tire test road routes appear to be at the threshold of thermal damage (i.e., between 1,300 and 1,400°F). The maximum recorded temperature for the in-use routes was 1,400°F and that occurred on the least severe driving cycle. It was measured to have a duration of no more than .04 percent of the time on the cycle. At first glance that would suggest that the temperature represents a spike and should not be cause for concern. However, over 50,000 miles the catalyst could be exposed to that temperature for well over an hour (assuming an average speed of 19.6 mph). The literature suggests that lean temperature excursions above 1,400°F for as little as twenty cumulative minutes can substantially impair catalyst performance.

The data are insufficient to determine whether in-use vehicles are thermally stressed to the point of severe catalyst damage. However, the little available data suggest that well-maintained vehicles do operate near the threshold of thermal damage. Many studies noted that "automotive catalysts are occasionally exposed to temperatures of

FIGURE 3-8

Comparison of Catalyst Inlet Temperatures Experienced on Different Driving Cycles



Vehicle: 1985 Chevrolet Impala equipped with a 5.0 litre/V8 engine and a three-way dual bed catalyst.

2,000°F for brief periods during their service". There are many conditions that can thermally stress a catalyst; they range from driving cycle to equipment malfunctions and can include:

- misfire due to spark plug fouling,
- partial ignition failures,
- rapid deceleration with fuel shutoff, and
- lean misfire due to intermittent injection system fouling.

High load conditions for extended periods of time requiring WOT operation can also produce high temperatures. EPA's In-Use Technology

Assessment (IUTA) program has investigated conditions that might lead to high temperature excursions. In 1986, EPA[8] conducted an analysis of the catalyst surface area observed on a sample of properly maintained 1981 and 1982 model-year vehicles. In that study, a minimum average specific surface area loss of 60 percent was observed for vehicles near their warranted useful life of 50,000 miles. The substantial loss in surface area for vehicles that were determined to have been well maintained indicated that the effects of poor maintenance (e.g., persistent misfire due to spark plug fouling, etc.), poisoning or plugging were not responsible. Therefore, EPA conducted an investigation into the sources of possible high temperature operation encountered under in-use conditions that are not included in the certification test.

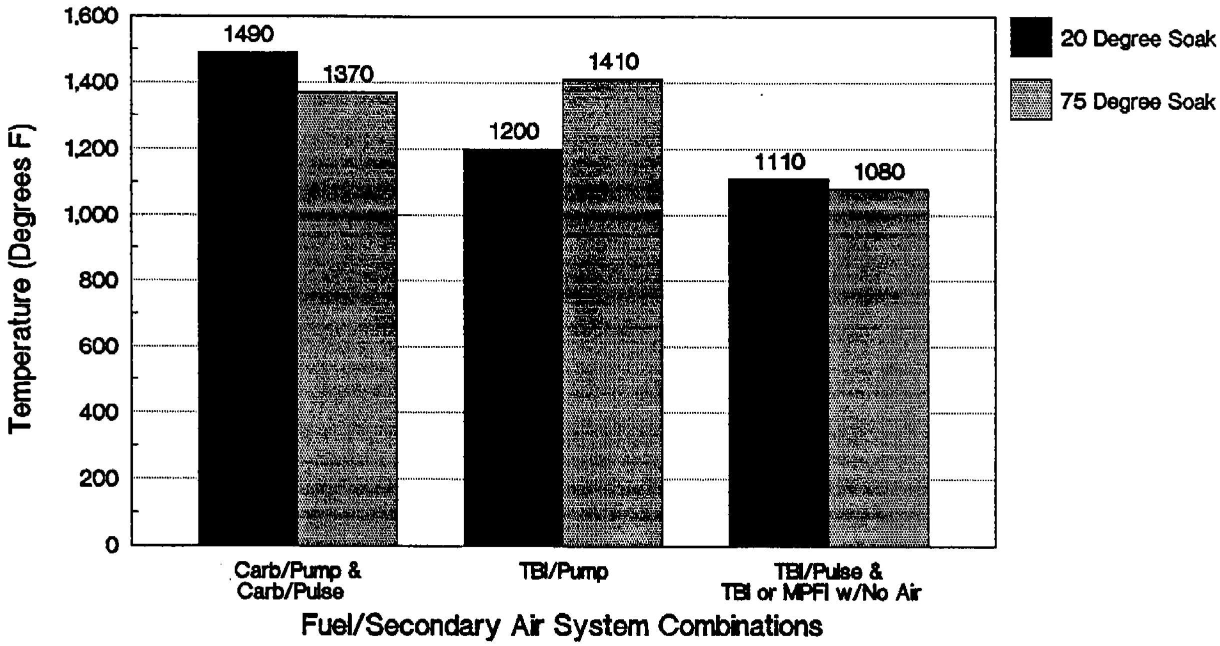
The effects of cold start operation were investigated to determine whether vehicles with secondary air systems reached temperatures where significant thermal damage could occur. The study was motivated by concern that under normal cold start conditions fuel systems are biased rich to aid starting and driveability. The poor combustion that occurs under those conditions leads to elevated HC and CO levels. Vehicles equipped with secondary air systems inject air to enhance light-off. The resulting exothermic reaction can lead to substantially higher temperatures than would otherwise be encountered under normal driving conditions. The cumulative effect of these short-term excursions was thought to be sufficient to cause catalyst damage.

The internal catalyst substrate temperatures of twenty-two 1983-1984 model-year, high-mileage, properly maintained vehicles were monitored over the FTP after nominal ambient air temperature soaks of 20°F. The results of that analysis are presented in Figure 3-9. It shows that during cold start operation, vehicles with fuel injection and reduced (pulse) or no secondary air experienced the lowest peak catalyst temperatures and that there was very little difference between peak temperatures for 20°F and 75°F soaks. The carburetor systems with air pumps or pulse air and throttle-body systems with air pumps experienced temperatures where the risk of thermal degradation has been shown to be a concern. (The cause of the higher temperatures recorded for the 75°F versus 20°F soak was not understood.) The high temperature excursions experienced by these vehicles substantially exceeded the peak temperatures that would be expected to occur during the durability driving cycle and may be sufficient to diminish catalyst performance.

The vehicles displaying the highest peak temperatures under cold start conditions, however, are not representative of current and future vehicle designs. Multipoint fuel injection (MPFI) is the predominant fuel system used on new cars, and all projections show it growing to well over a 90 percent share of the automobile market by 1990. Most current vehicles use single-bed three-way catalysts and do not have a need for secondary air. Thus, while the EPA study points to concern about the temperatures that the catalysts may experience when

Figure 3-9

Comparison of Peak Catalyst Temperatures During Cold Start Operation



Source: Zerafa, et al., SAE Paper #880105, 1988

secondary air is present, it is not clear that the same concern should be applied to current and future vehicle designs.

MPFI systems have been shown by EPA to achieve substantially reduced CO levels under cold start conditions. The reason for this reduction is that MPFI systems are able to more carefully meter the enrichment necessary to overcome cold start problems. This increase in control is translated into lower HC and CO levels which in turn reduce the potential for high temperature spikes under cold start conditions. Evidence of this control is the small difference between the peak temperatures measured after 20°F and 75°F soaks.

3.3 Summary and Conclusions

Several conversations were conducted with catalyst manufacturers and automobile manufacturers to confirm the above findings. There was general agreement about the trends noted and the basic thermal deterioration mechanisms. The only disagreement was over the threshold temperature at which catalyst damage begins to occur. Auto industry sources maintained that the threshold temperature was 1,400°F. Catalyst manufacturers suggest that it is in the range of 1,600 - 1,800°F and point towards recently developed catalysts for European vehicles and heavy-duty trucks as proof of the ability of the new catalysts to perform in the higher temperature environments. Little data are available on the performance of these vehicles.

With the existing data, it is not possible to determine which source is correct; however, the following conclusions can be reached:

- The threshold for catalyst damage is lower under lean conditions than it is under rich conditions. Lean high-temperature excursions have been shown to significantly affect Rh interactions with alumina, and Pt and cerium oxide crystal growth. The primary impact of these interactions is a loss of CO and NOx conversion efficiencies at and rich of stoichiometry.

- The trend towards exclusive use of MPFI systems with single-bed three-way catalysts and elimination of secondary air will significantly reduce the chances of lean high temperature occurrences. It also places increasing reliance on Rh for the conversion efficiency of all three pollutants.

- The primary cause of thermal deterioration is lean misfire which can elevate catalyst temperatures to above 2,000°F. No data are available to quantify the frequency with which these conditions occur. The data suggest that rare events leading to high temperature excursions may be responsible for much of the thermal damage that has been identified in the field. Many circumstances can be theorized to occur under in-use conditions that lead to high temperture conditions. These include rapid declerations, major ignition system problems which lead to misfire and minor ones which lead to partial incomplete burns, and intermittent injection system fouling.

- The AMA cycle has been shown to produce catalyst temperatures that are not representative of in-use driving conditions. The lack of thermal stress on the durability test could be a significant source of the difference in deterioration experienced between certification and well-maintained vehicles. The representativeness of the temperatures that catalysts experience on the durability cycle needs to be improved.

- The representativeness of the durability temperatures will become more important as manufacturers move catalysts closer to the engine to comply with more stringent emission standards (e.g., the current range of proposals/bills being considered by Congres,s and ARB's proposed standard of 0.25 g/mi HC). By reducing the distance from the engine to the catalyst, the time required to achieve "light-off" will be decreased and the catalyst will convert a larger portion of the emissions generated under cold start conditions.

- To improve the representativeness of the thermal stress that catalysts receive on the durability cycle, engine loads will have to be increased. Several options are available to accomplish this goal: one would be to operate vehicles on uneven terrain; the other would be to add more frequent and severe accelerations to the durability cycle. Both represent a significant departure from current mileage accumulation procedures.

- The collection of data characterizing temperatures that catalysts experience under in-use conditions and on AMA cycles is needed to support the development of improvements to the AMA cycle. It would produce a better understanding of the causes of deterioration that well-maintained vehicles experience under in-use conditions. It could also be used to aid decisions about the ability of manufacturers to achieve more stringent emission standards. The ability of current catalysts to withstand higher temperatures would provide insight into the feasibility of setting more stringent standards.

4.0 CHEMICAL POISONING

Commercial-grade unleaded gasoline contains trace amounts of lead (Pb), phosphorus (P), sulfur (S), manganese (Mg) and silicone (Si). The effect of these elements on emission control system performance has been discussed extensively in the literature. The reader is referred to the Task 5 report (Volume II, Section 6) for a summary of those effects. This section will not repeat all of the information presented there, but instead will discuss the effects of these elements on catalyst durability in order to provide a contrast with the effects of thermal degradation. Additional data on the effects of P contained in engine oil are also presented.

In general, the effects of chemical poisoning on catalyst durability and performance are quite different from those of thermal aging. The elements, contained in some combination of gasoline, oil and aftermarket additives, have two primary avenues to the catalyst. The first route is passage through the combustion chamber with sources including fuel contaminants and leakage through rings, intake valve seals, and PCV valves. The second route is a noncombustion route from leakage through exhaust valve seals. The difference between the two paths is that in the first the contaminants are at least partially oxidized, whereas in the second the contaminants enter the catalyst in an uncombusted form. Both routes lead to deposition on the catalyst surface as part of the exhaust gas.

The actual effects of the deposited elements on catalyst performance are quite complex and dependent on the concentration of the elements in the exhaust gas, catalyst composition, thermal history and stoichiometry of the exhaust gas. The primary effect of chemical poisoning is to coat the surface of the catalyst and retard the rate of exhaust gas diffusion to active metal sites. This is in sharp contrast to thermal deactivation where the primary effect is to reduce the number of active metal sites. Poisoning, therefore, has the greatest impact on diffusion-controlled reactions: HC conversion throughout the range of exhaust stoichiometry; and through more complex interactions with thermal mechanisms on NOx conversion. A secondary effect of poisoning is that it increases the amount of time required for a catalyst to light-off.

Most of the recent studies of the effects of poisoning have focused on the rate of deposition and the related effect on diffusion and pollutant conversion efficiency. Little information is presented on the differential effects of the poisons on individual Noble metals or support materials. Instead, most studies address the conversion efficiency of conventional (three-way) Pt/Rh catalysts for individual pollutants.

4.1 Lead

Pb deposition on the catalyst is affected by two different forms of fueling behavior:

- build up from continuous exposure to trace levels in unleaded gasoline; and

- use of leaded gasoline, commonly referred to as misfueling.

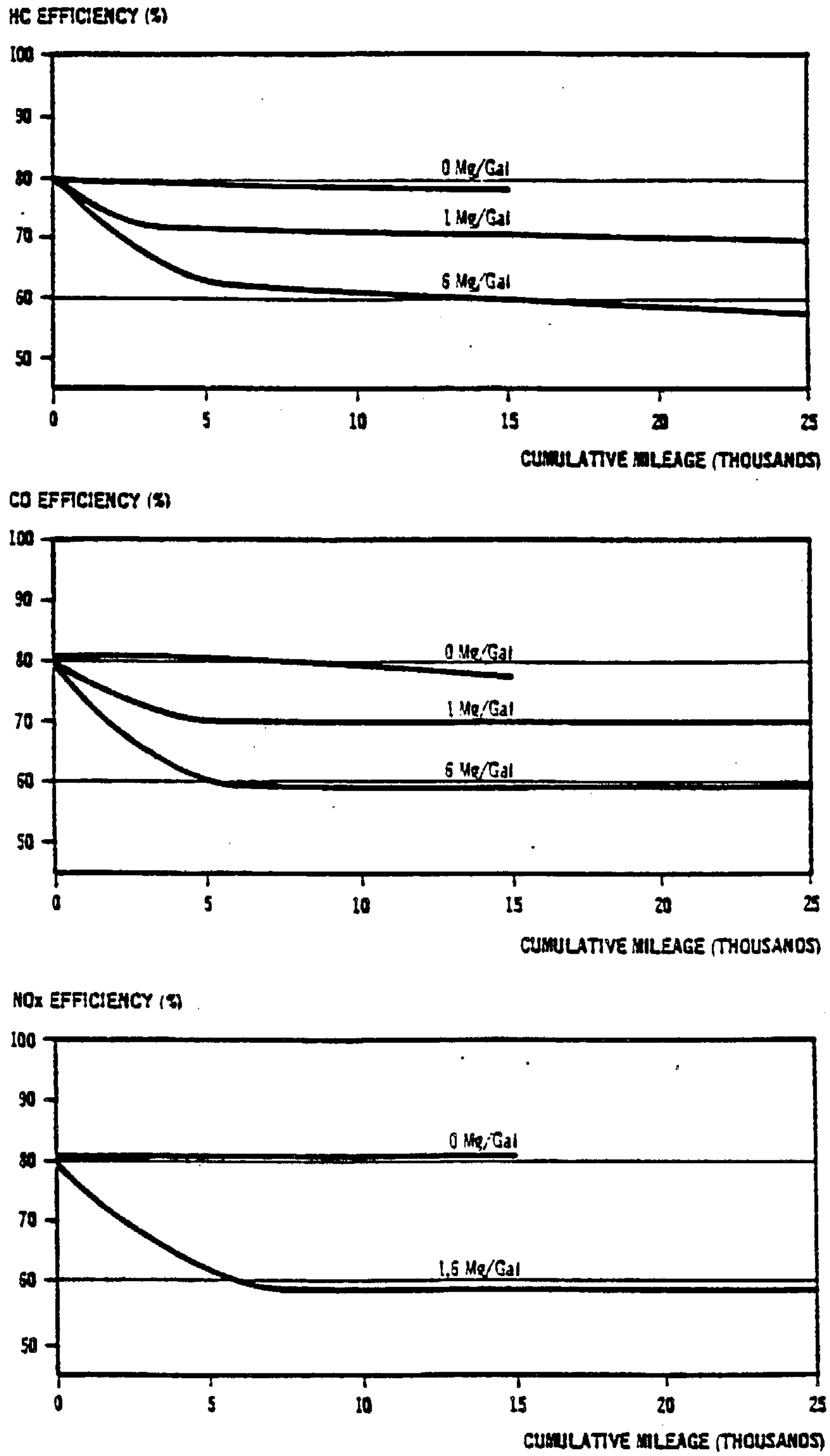
Traditionally, the effect of misfueling has been to subject the catalyst to a large volume of Pb in a very short period of time. The actual exposure was dependent on the frequency at which a particular vehicle was misfueled and the Pb content of the fuel. The imposition of lead phase-down regulations have significantly reduced the Pb content difference between leaded and unleaded fuel. The Pb content of leaded gasoline has gone from more than 2 gm/gal in the 1970's to the current regulated level of 100 mg/gal. At the same time, the regulations governing the Pb content of unleaded fuel have remained at 50 mg/gal. Thus, there is little difference between the Pb content of both fuels. To determine the effect on Pb on catalyst durability of current and future vehicles, it is necessary to discuss the effect of very low or trace Pb levels.

Through a review of the literature and conversations with catalyst manufacturers, it is apparent that Pb has a substantial impact on catalyst performance even at trace levels. As discussed in the Task 5 report, few papers have addressed the effects of trace Pb levels on conversion efficiency; when the Pb content of leaded gasoline was measured in grams, most analyses were focused on the effect of misfueling . However, several studies, conducted by Ford[1,2], show reductions in catalyst efficiency at Pb levels between 1 and 10 mg/gal. A 1979 paper showed a 10 percent reduction in HC conversion efficiency after less than 5,000 miles when using gasoline with 1 mg/gal Pb levels.

That study artifically aged three-way catalysts to an equivalent of 25,000 miles on iso-octane fuels containing trace levels of Pb, P, and S. Figure 4-1 shows the conversion efficiencies measured at 500°C (932°F) under steady-state conditions. The upper line for each pollutant contains no Pb and shows little deterioration through 15,000 miles of operation with 0.8 mg/gal of P and 0.03 percent S. The addition of Pb, however, at 1 and 6 mg/gal is shown to cause substantial reductions in catalyst efficiency for all pollutants. Because the measurements were taken at steady-state conditions, it is thought that if the effects of light-off were included, even greater deterioration would have been measured.

Sierra has been unable to find any data documenting the effect of trace lead levels on the performance of the oxygen sensor. A study by Bosch[3] addressed oxygen sensor performance with higher lead levels (e.g., 1.5 g/gal and greater). They showed that there are two effects of Pb on the sensor performance. The first is that it coats the

FIGURE 4-1
EFFECT OF RESIDUAL LEAD ON PEAK CATALYST EFFICIENCIES



Source: SAE Technical Paper Series. No. 790942 surface of the sensor and reduces the diffusion of exhaust to the sensor surface. This has the effect of changing the shape of the static output curve of the sensor so that the output voltage jump does not occur at $\lambda=1$ but at a richer value as shown in Figure 4-2. The second effect of Pb is to increase the response time for both rich-to-lean and lean-to-rich shifts. At low temperatures, the effect of this increase is small, but at temperatures over 700°C the lean-to-rich shift time becomes extremely large. The combination of these effects results in a rich-biased air fuel ratio and an increase in engine out HC and CO levels.

It is clear from the preceding data that catalysts are extremely sensitive to Pb poisoning and that even the trace Pb levels legally allowed in unleaded gasoline are responsible for a reduction in catalyst efficiency for all in-use vehicles. Contacts with catalyst manufacturers and automobile manufacturers confirmed that one of the best opportunities to increase the life of existing and future catalysts is to reduce the amount of lead contained in commercial unleaded gasoline. Based on these data, it is apparent that the best strategy would be a total ban on the Pb content of unleaded gasoline. New standards should be set on the basis of the lowest practical limits that can be achieved when the two fuels share the same transportation and storage facilities. Using the relation of past fuels as a guide to that limit (i.e., 2 gm/gal leaded and 50 mg/gal unleaded), it appears that when leaded fuel contains no more than 100 mg/gal the standard for unleaded should be no greater than 2.5 mg/gal.

One source of information on the Pb levels in unleaded gasoline is MVMA's fuel surveys. It shows that the Pb levels in unleaded gasoline have been steadily declining since the peak value recorded in 1979.

Unleaded Regular

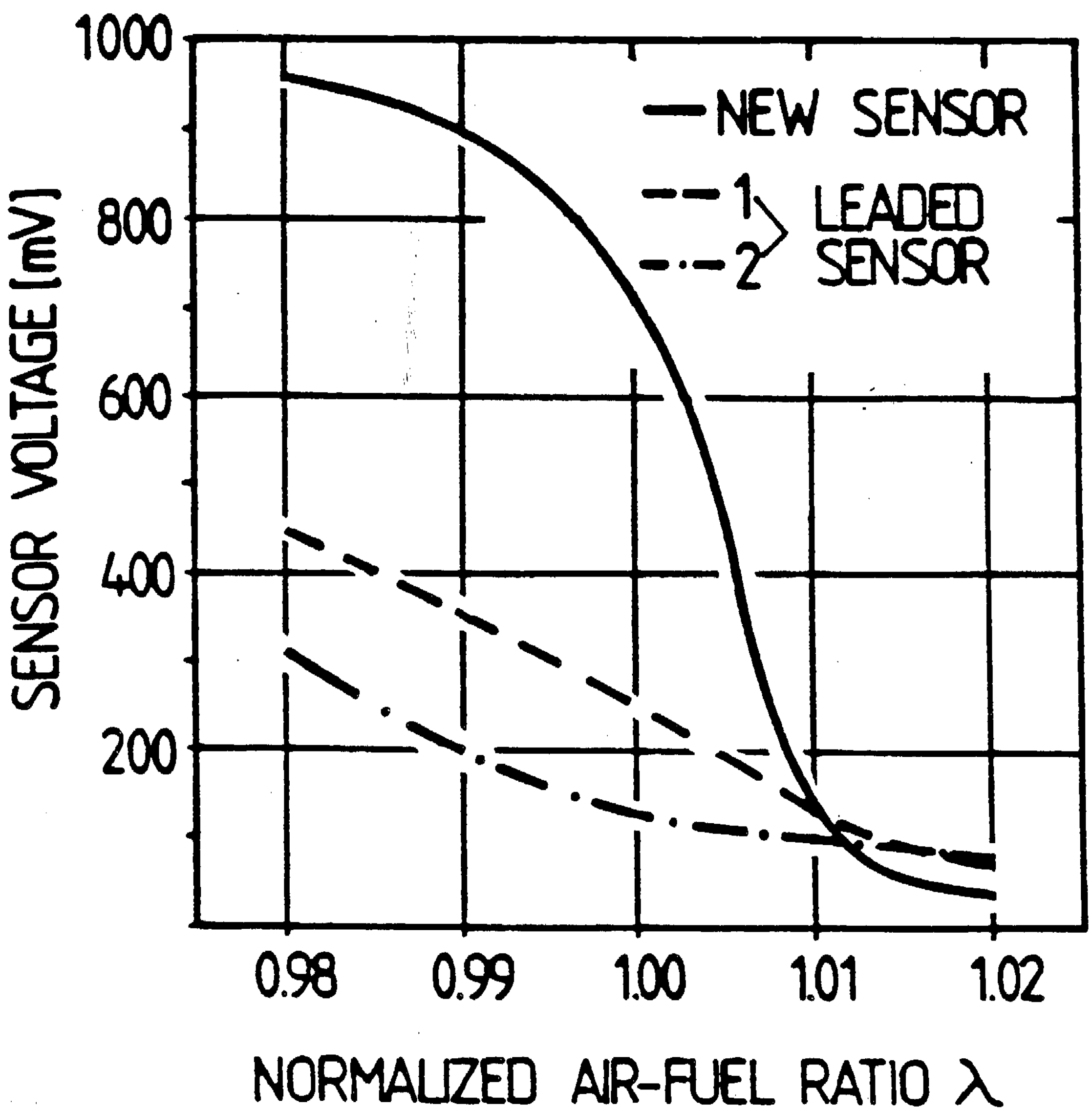
Year	g Pb/gal
1979	.016
1980	.011
1981	.011
1982	.005
1983	.003
1984	.003
1985	.002
1986	.002
1987	.001

The 1 mg level recorded in 1987 is the lowest level reported in the survey. It indicates that as unleaded gasoline has increased its market share and as Pb levels in leaded gasoline have declined that the unleaded Pb levels have also steadily declined. The low level recorded in 1987 (EPA did not have the results of the January 1988 survey) indicates that the long-term Pb poisoning may not be a significant problem. The poisonous effects of 1 mg levels of Pb, however, are significant over extended periods of time. The low Pb levels achieved in the recent survey indicate that compliance with

FIGURE 4-2

Excessive rich shift of static Lambda characteristic at 550° C of a sensor after 1 000 km run in a cold V8-engine with leaded (0,15 g/l) gasoline (curve 1).

Curve 2: The same sensor after heating for 10 minutes at 850° C



Source: Bosch

standards below the current 50 mg/gal level are not an issue. The only problem in setting standards at such low levels may be difficulty in developing low cost tests to accurately monitor them.

4.2 Phosphorus

P is a catalyst poison which blocks the diffusion of exhaust gas constituents to active metal sites on the catalyst. There are two sources of P entry into the exhaust gas stream: trace contamination of unleaded gasoline; and engine oil antiwear additives. The legal limit of P in unleaded gasoline sold in California is 5 mg/gal. Based on a review of the literature, the Task 5 report reached the conclusion that fuel-based P has minor effects on catalyst performance. Conversations with automobile, catalyst and engine oil additive manufacturers support that finding. The effect of oil-based P on catalyst performance is much more severe and controversial. The literature contains numerous studies of the effect of oil-based P on catalyst performance.

P enters engine oil primarily through zinc dithiophosphate (ZDP), the primary antiwear and antioxidant additive. The P contained in ZDP has long been known to reduce catalyst conversion efficiency. A 1976 GM[4] analysis of engine oil additives on oxidation catalyst efficiency found that conversion efficiency decreased linearly with increased amounts of P found on the catalyst. Table 4-1 summarizes those reductions in conversion efficiencies for HC and CO at 50,000 miles.

The results show that relatively large reductions in catalyst efficiency are possible under high oil consumption patterns, particularly for CO. The authors also found that the presence of calcium sulfonate, a detergent, enhanced the accumulation of P in the sump pump and reduced the amount of P retained on the catalyst; the effect, however, was found to be inadequate.

It should be remembered that the data in Table 4-1 were developed with high oil consumption rates on very early catalysts and that many of the parameters affecting these results have changed since the early experiments. Discussions with one of the authors pointed out the following changes that have occurred to temper those findings:

- Catalyst formulations have changed substantially with reduced noble metal loadings and better dispersion of active metals in the washcoat. The increased dispersion decreases the chances of deactivation from all poisons.

- Engines have "dried up", that is, the oil consumption levels experienced by mid-1970 engines ranged at about 1,500 miles per quart. Late-model vehicles typically have oil consumption levels of 3,000 to 7,500 miles per quart. Less P is passing through the engine to the catalyst.

- Under prodding from automobile manufacturers, the P levels contained in engine oils have declined; again the source of exhaust gas P contamination has decreased.

TABLE 4-1

Predicted Conversion Efficiencies After 50,000 Miles

Phosphorus Concentration in Engine Oil, Wt.%	Phosphorus Added To Engine, Grams	Conversion Efficiency HC	Conversion Efficiency CO
0	0	84	93
	Oil Consumption = 1,000 mi/qt		
0.10	40	74	74
0.15	60	70	69
0.20	80	69	66
	Oil Consumption = 2,000 mi/qt		
0.10	20	79	81
0.15	30	76	77
0.20	40	74	74
	Oil Consumption = 4,000 mi/qt		
0.10	10	81	87
0.15	15	80	86
0.20	20	79	81

Many studies of the effect of P on catalyst performance have been conducted over the past ten years. Unfortunately, the findings in these papers on the mechanisms of P poisoning have not been entirely consistent. Recent studies have not addressed the relative effect of different engine oil P levels (wt. %) on catalyst durability, instead they have addressed the following concerns:

- Comparing the influence of combusted versus non combusted ZDP - is the P effect on catalyst durability influenced more by oil leakage from the intake valve seal or the exhaust valve seal?

- Determining the temperatures at which P sinters to form a glassy layer that plugs pores and severely retards diffusion.

- Determining whether the amount of P deposited on the catalyst is the primary determinant of catalyst deactivation or whether additional but related deposits (e.g., Zn, Ca, etc.) affect catalyst performance.

- Determining whether the effect of P is reversible.

- Finding additive formulations that can reduce the deposition of P on the catalyst and/or elevate the temperatures at which it sinters.

- Finding alternative antiwear/antioxidant additives that can reduce the amount of ZDP and therefore P in engine oil.

Several studies have suggested that the greatest catalyst deterioration due to P deposition occurs when the catalyst is exposed to exhaust gases containing noncombusted ZDP. A 1984 Ford[5] study indicated that the loss of catalyst activity was much more severe when exhaust valve seals were removed than when inlet valve seals were removed. It also indicated that the formation of glassy deposits occurred at catalyst temperatures of 450°C (842°F) and that at higher temperatures (i.e., 750°C or 1.382°F) the glassy deposits were not found. The primary effect of the deposits was to increase the light-off temperature for HC.

A 1987 analysis conducted by Ciba-Geigy[6] in association with Ford showed that non-combusted ZDP caused a similar glaze formation at temperatures from 450-730°C (842-1,382°F). It also showed that after 8,000 miles of simulated operation with an oil consumption rate of one quart per 1,000 miles, catalyst conversion efficiency was reduced to less than 21 percent for HC, CO and NOx. The light-off temperature for this catalyst was measured to be 440°C. Unfortunately, the P content of the oil was not noted. Nevertheless, the analysis shows that the effect of uncombusted ZDP on catalyst performance can be extremely severe.

A 1985 analysis by Signal Automotive[7] found, in contrast to the above studies, that three-way catalyst deactivation was most severe when the intake seals were removed. Lower conversion rates for intake versus exhaust valve seal removals were noted for all three pollutants when catalysts were aged at low temperatures (427°C or 800°F). Rapid catalyst deactivation was noted, however, when either seal was removed. The study concluded that "although low melting zinc phosphate glasses form on the catalyst surface after low temperature aging with the ZDP oil additive, they are only partially responsible for the P induced deactivation" observed. Additional Zn-P species were identifed in catalyst depositions and found to be responsible for catalyst deactivation. The paper ended by concluding that it was not possible to reactivate the P-deteriorated catalysts with either rich or lean conditioning at temperatures up to 760°C (1,400°F).

A 1985 study by Mazda[8] addressed the mechanisms of oil-based P poisoning effects on both pelleted and monolithic three-way catalysts. That study focused on the effects of <u>deposits derived from engine oil</u>

combustion. It found that P, Pb, Zn and Ca catalyst deposits increased linearly in proportion to vehicle mileage. P was found to have the largest amount of material retained by both monolithic and pelleted catalysts. The level of P deposition, however, was not the definitive indicator of loss in catalyst efficiency. The analysis showed that the primary measure of P poisoning is the morphology of the deposits, that is, the porosity of the surface. As the deposit surface becomes more dense and less porous, less exhaust gas is able to diffuse into the interior of the catalyst and come in contact with the active metals of the washcoat. This leads to a progressive loss in conversion efficiency as the deposit density increases. The highest density deposit has a glassy layer with virtually no porosity. Several parameters were found to govern the vitrification of the P deposits:

- At lower temperatures the P deposit accumulates on the surface of the catalyst in the state of powder. At higher temperatures which are encountered in normal operation (i.e., 750 to 850°C or 1,382 to 1,562°F) the powder sinters into a high-density glassy layer that does not recover its previous powdery state when the temperature is lowered.

- As the ratio of metals (e.g., Ca, ZN, Mg, and Ba) to P becomes higher, the temperature of vitrification increases.

- The higher the P content, the lower the vitrification temperature.

The analysis also found that the best remedies to prevent the formation of glassy deposits were to:

- increase the amounts of metal additives (detergents) in engine oil;

- hold the catalyst temperature below the vitrification temperature; and

- reduce the P content of engine oil. This has the effect of reducing the P level in exhaust gas and increasing the metal/P ratio (M/P ratio) entering the catalyst.

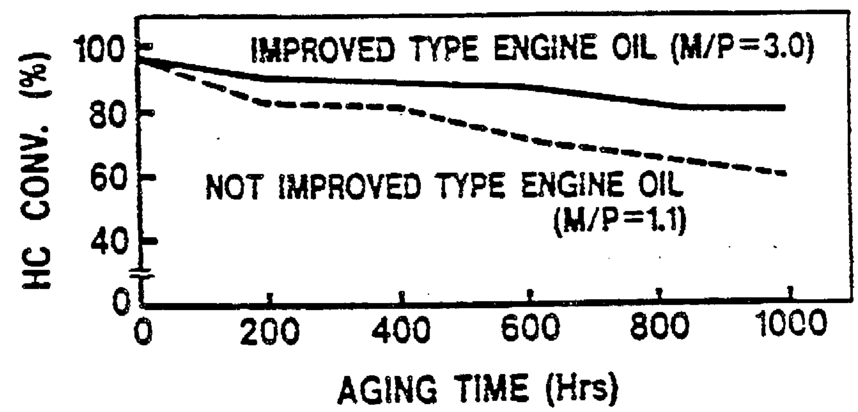
Experiments were conducted with several detergents to evaluate their effect on the rate of catalyst deterioration. The results showed that it was possible to decrease the rate of deterioration in HC conversion efficiency that engines experience over a modified AMA cycle. Figure 4-3 shows the effects of oil containing the higher M/P ratio relative to a commercial grade oil.

Similar analyses of the effect of ZDP on catalyst efficiency have shown that improvements are possible with the addition of antiwear additives to ZDP. The literature indicates that no successful substitutes for ZDP have been found. Several formulations have been developed that allow ZDP content to be reduced but not eliminated.

FIGURE 4-3

Effect of Engine Oil on HC Conversion at 10 Mode Cycle

(Modified AMA Cycle on Dynamometer)



Source: Yoshinori Niura and Kenji Ohkubo, SAE Paper #852220 1985

Conversations with domestic manufacturers indicate that they are skeptical of the ability of engine oils to prevent wear at levels below 0.8% wt. P. Several automobile manufacturers in the U.S. and Europe have actually placed lower level P limits, usually in the .08% wt. range, to protect engine durability.

Recognition of the poisonous effect of the P contained in ZDP has led manufacturers to call for reductions in engine oil P levels. The Japanese manufacturers have been quite aggressive in setting chemical restrictions on motor oil. Table 4-2 provides a summary of their restrictions[9] and shows clear differences in standards for vehicles produced for use in the Japanese home market versus those for the U.S. market. Unconfirmed conversations with additive producers indicated that this reflects more of a difference in the metallurgy of the products than a concern for catalyst durability. An unofficial engine oil P standard of .10% wt. has evidently been set for Australia. Conversations with U.S. manufacturers indicate that they too have been active in pushing for lower P levels. Current domestic factory fill specifications appear to be .10% wt.

Conversations with additive and automobile manufacturers indicated that P levels have been decreasing in recent years. The current P levels in the U.S. and California oils are normally distributed around .12 percent wt. with bounds of .10 and .14 percent wt. The actual distribution is unknown because the P levels in oils are not

TABLE 4-2

Chemical Restrictions on Motor Oil

Car Manufacturer	Phosphorus (% Wt.)	M/P Ratio
Toyota		
Factory Fill for Domestic	0.05 Max	1.0 Min
Export to U.S.	0.10 Max	1.0 Min
Export to Ex. U.S.	0.05 Max	1.0 Min
Genuine Oil	0.05 Max	1.0 Min
Service Fill	0.10 Max	1.0 Min
Nissan All	0.10 Max	1.0 Min
Mazda		
Mono Grade	0.045-0.055	3.0-4.0
Multi Grade	0.065-0.075	2.0-3.0
Honda All	0.10 Max	-
Subaru		
Factory & Service Fill	0.09-0.12	-

monitored, instead they are estimated from ZDP levels. A recent development that is certain to influence near-term P levels in engine oil was the setting by API in March of 1988 of a new, more stringent engine oil test procedure, SG. That procedure is the result of a tripartite effort by API, SAE and CRC to determine the ability of engine oil to prevent wear in late-model vehicles. Automobile manufacturers, through SAE, evidently requested the change because of recent increases in the length of engine/powertrain warranties and concerns over the ability of oils to prevent wear in new vehicles. The implementation of the new test will arrest the decline in P levels, because the increased stringency will eliminate further reductions in ZDP content. Thus, it appears that the range of .10 - .14 %wt. P content will remain the same or possibly increase unless regulatory action is taken to mandate lower levels.

Additive manufacturers indicated that it is possible to reduce P levels to .10 without a substantial increase in cost or shift in chemistry. Evidently, more precise metering of the ZDP content is required and additional additives would be needed to provide oxidation and wear protection for the loss in ZDP. Additives represent roughly 10 percent of the cost of engine oil; therefore, setting a P standard is unlikely to have a significant impact on the cost of oil.

Conversations with domestic manufacturers indicated that no studies of the effect of alternative engine oil P levels have been published in recent years, because their analysis has trouble discerning the effect of a P difference of .10% wt. They attribute this difficulty to improved catalyst formulations and the reduction in oil consumption of late-model vehicles.

A task force[10,11] was organized by SAE's Fuels and Lubricants Technical Subcommittee to investigate the need for lower engine-oil P levels in the 1984. Membership included representatives of catalyst manufacturers, oil additive manufacturers, refiners, automobile manufacturers and interested parties. Conversations with the chairman and secretary of the committee indicated that an extensive volume of data was collected over the one-and-a-half-year life of the committee. At the time, there was extensive interest in reducing the engine oil P levels because of concern about catalyst durability. Information was collected on the range of engine-oil P content levels available in the market and their effect on catalyst durability over 50,000 miles, "the design life of the catalyst". The information showed some degradation on the order of 10 to 15 percent for 0.12 to 0.14 % wt. P content engine oils. The impact was considered tolerable, particularly given manufacturer concerns over loss of valve train and cam shaft wear increases that would occur with further reductions in engine-oil P levels. There were conflicts in the data presented, with some showing a reduction in conversion efficiency and others showing little or no impact. The data were felt to be insufficient to make a strong recommendation on engine-oil P content. The committee tried to get funding to conduct a series of tests to determine a target P content level that minimized degradation. Because of conflicts among committee members over the need for further analysis, the funding was not obtained. Therefore, the committee ended by making a recommendation that the P content of engine oils be reduced without specifying a target value, and that the alkaline metals content of the additive be increased, also without specifying a target. That recommendation is now a part of J123 in the SAE handbook.

Conversations with manufactureres indicated that they must use oils with P levels that are representative of oils available in the aftermarket in their durability vehicles. Conversations with EPA's Ann Arbor laboratory indicated that they do not monitor engine oil P levels.

Based on the evidence of the effect of engine oil P content on catalyst conversion efficiency, international trends in P engine oil standards, and conversations with additive manufacturers it is clear that lower P levels can be mandated. Unfortunately, little data are available to quantify the range of P levels that currently exist in the market, less data are available to quantify the benefit of reducing those levels.

4.3 Sulfur

No new information can be presented on the effect of S on catalyst durability beyond that presented in the Task 5 report. Briefly, the primary effects of S on three-way catalyst performance are as follows:

- The effect of S found in commercial fuels has been found to reduce catalyst efficiency by a few percent.

- Poisoning due to S is reversible; once the S in fuel is removed, the catalyst returns to its previous efficiency level.

- S poisoning tends to affect HC and NOx conversion more significantly than CO conversion.

- Under rich operating conditions, S in the exhaust is converted to hydrogen sulfide (H_2S). Under lean operating conditions, SO_2 and SO_3 are formed. At temperatures below 600°C and lean operating conditions, S reacts with ceria to form Ce(III) sulphate. At temperatures above 600°C (1,112°F) or when the air fuel ratio switches rich to lean, the previously stored S is released and reacts with H_2 to form H_2S.

While a reduction in the sulfur content of gasoline is desirable because of reductions in H_2S, sulfate and SO_2 emissions, the effect on catalyst conversion efficiency would be minimal.

4.4 Manganese

The Task 5 report found that all analyses of Mn effects on catalyst performance were related to the use of MMT. The results of these studies showed that there is a difference of opinion as to its effect on catalyst performance. The effects range from significant reductions in NOx conversion efficiency to improvements where the combustion of MMT to Mn_3O_4 served as a scavenger for transporting catalyst poisons including P, Zn and Pb. No additional data are available to quantify the effect of Mn on catalyst activity.

4.5 Silicon

As discussed in the Task 5 report, Si compounds have deleterious effects on both the oxygen sensor and the catalyst. At high temperatures, Si decomposes to form amorphous silica which deposits on the surface of the catalyst and blocks the diffusion of exhaust gas and can ultimately plug the monolith. The effect of Si deposition on the catalyst surface is irreversible. Laboratory measurements of three-way catalysts using fuel doped with 20 ppm silicone resulted in conversion efficiencies of less than 40 percent for all three pollutants after 15,000 simulated miles of operation.

The effects of silica deposits on oxygen sensor performance are similar in that diffusion of the exhaust to the surface is blocked. This results in an increase in the output voltage of the sensor at a given air fuel ratio. As with Pb poisoning, the response time for the sensor is also slowed, particularly for the rich to lean shift. While instances of Si contamination have occurred in the U.S., no information is available documenting occurrences in California.

4.6 Summary and Conclusions

The data presented suggest that the primary poisons that affect catalyst durability are the trace Pb levels contained in both leaded and unleaded gasoline and the P contained in engine oil antiwear/antioxidant additives. The remainder of the suspected poisons have been shown to have little effect on catalyst durability because either: the effects are reversible, as in the case of S; the effects are not clear, as in the case of Mg; or the effects are significant but the level of fuel contamination is extremely small and poorly documented, as in the case of Si.

Based on the data presented in this section, it is difficult to compare the effects of Pb and P because of the poor documentation of alternative P level effects. Several studies noted catalyst retention of P is the greatest of any of the deposit constituents. That finding must be tempered by the fact that P is a "non-specific" poison in that it does not seek active metal sites for deposition. Instead, its deposition is influenced by flow rates, surface geometry and temperature gradients. The large surface areas in the catalyst that do not contain active metals diminish part of the effect of the deposition. In contrast, Pb is a "specific" poison in that it is selectively deposited directly on active metal sites as HC is oxidized. Thus, small amounts of Pb, as discussed earlier, can exert a significant impact on catalyst activity.

The data collected by MVMA and EPA on the Pb levels of unleaded gasoline indicate that Pb is not a significant problem. They also suggest that imposing a standard of 2.5 mg/gal would have little effect on catalyst performance. Nevertheless, the Ford analysis shows that trace levels of 1 mg/gal can have a 10 percent effect on catalyst performance in approximately 5,000 miles. Because of the extreme toxicity of Pb to catalyst performance, Sierra recommends that ARB set a target for the complete elimination of Pb from unleaded gasoline and work with refiners to achieve that goal. The effect of such a program, even if it is phased-in over an extended period of time, will be to eliminate a significant source of long-term, low-level catalyst deterioration. A major constraint in setting the standard will be the measurement error and cost of equipment used to enforce the standard.

The confusion over the mechanisms of engine-oil-based P poisoning and the dearth of information on the effects of alternative P levels on catalyst performance make it difficult to target a specific reduction in P levels. There is clear agreement among all manufacturers that P is a poison that reduces catalyst efficiency. The only difference is over the level of P in engine oil that can reasonably be tolerated. Some Japanese manufacturers have clearly decided that lower P levels with a higher alkaline metals content are the best approach to minimize the formation of P deposits on catalysts. In general, without being specific as to the level, SAE has supported both of these positions. The introduction of a more stringent antiwear test for engine oils has reversed the trend in declining P levels in recent years and may in fact lead to a short-term increase. Conversations with engine oil additive manufacturers indicate that P levels of .10% wt. can be achieved without significant cost increases. Several papers in the literature have suggested that it is possible to achieve lower levels and there is the example of the lower oil specifications put forward by several Japanese manufacturers. With this background, despite specific data from manufacturers on the effects of alternative P levels, it would be wise for ARB to pursue a rulemaking that sets an upper P limit of .10% wt. in engine oils. The long-term effects of extended exposure to P, while it has been minimized, is bound to contribute to minimizing long-term catalyst deterioration.

5.0 ESTIMATES OF IN-USE DETERIORATION

The preceding discussions of the mechanisms of catalyst deterioration and the range of impacts observed under laboratory conditions provide insufficient insight into the extent of deterioration that catalysts are experiencing under in-use conditions. This section develops estimates of the aggregate deterioration that vehicles are experiencing over the first 50,000 miles of service. The relative contributions of increased engine out emissions and catalyst deterioration to overall vehicle deterioration are then discussed. The section concludes with an estimate of the share of the emissions inventory in the year 2000 that will be caused by vehicle deterioration.

5.1 Computation of Deterioration

Little data are collected by regulatory agencies to quantify the deterioration that catalysts experience from in-use conditions. Almost all data collection efforts focus on the FTP performance of the vehicle, not the catalyst. To quantify changes in catalyst efficiency, measurements of emission levels must be taken both before (i.e., engine out) and after the catalyst. The ratio between the two values provides a measure of the catalyst efficiency. Neither EPA's nor ARB's surveillance program collects this information.

A 1980 analysis conducted by EEA[1] for the National Commission on Air Quality provided an estimate of the change in catalyst efficiency between 5,000 and 50,000 miles. Using certification data and deterioration rates supplied by Ford, and the assumption that engine out emissions remain essentially constant over 50,000 miles EEA generated the estimates contained in Table 5-1. Generally, it showed that very little deterioration occurred for either HC or CO for any of the systems displayed. The loss of NOx conversion efficiency is greater, particularly for the dual-bed vehicles.

Sierra believes that it is inappropriate to assume that engine out emissions remain unchanged over the first 50,000 miles of operation. As discussed in the section on thermal degradation, intermittent ignition or injection system problems can cause temperature and engine out emission increases. In addition, gradual restrictions in exhaust gas contact with the oxygen sensor due to either thermal or chemical poisoning can lead to changes in engine out emissions. In addition, the Task 5 report showed that fuel injector plugging can be a problem for in-use vehicles because of the thermal cycling that injectors receive. Vehicles operating on the AMA cycle do not experience similar levels of thermal cycling and therefore do not exhibit the injector plugging that some in-use vehicles experience. These issues suggest that to better understand the extent of both system and catalyst degradation the performance of in-use vehicles should be compared with certification vehicles.

TABLE 5-1

Summary of Normal Catalyst Deterioration (Conversion Efficiency in Percent)

System	Mileage	HC	CO	NOx
Oxidation	5,000	85	90	--
	50,000	76	81	--
Three-way (FBC + EGR)	5,000	83	60	62
	50,000	78	55	55
Three-way (EFI)	5,000	87	78	95
	50,000	82	71	84
Dual-bed (Closed-loop)	5,000	91	90	47
	50,000	87	85	25
Dual-bed (Open-loop)	5,000	80	85	40
	50,000	70	76	22

To estimate the overall deterioration that vehicles experience under in-use conditions, the emissions of certification vehicles are compared with vehicles identified by ARB inspectors in surveillance programs as not having been tampered. Data collected in surveillance programs 1-8 have a field where inspectors indicate whether vehicles have been tampered. Those vehicles receiving a "N" in that field were selected for inclusion in the analysis. The actual maintenance history of these vehicles is unknown and it is not clear if they would satisfy a formal definition of "well maintained". They do, however, represent a broad spectrum of operation and are used to estimate the performance of all in-use vehicles in the development of emission factors. To aid the analysis, the non-tampered vehicles were organized into the same technology categories that are being used to develop emission factors for the I/M model[2]:

- 1977-79 throttle body (TBI)/Carburetted (CARB) with three-way catalysts (TWC's);
- 1980 TBI/CARB with TWC's;
- 1981+ TBI/CARB with single-bed (SB) TWC's
- 1981+ TBI/CARB with dual-bed (DB) TWC's
- 1977-80 multipoint fuel injected (MPFI) with TWC's
- 1980+ MPFI with TWC's.

The categories were selected to represent emission control technologies of current and future vehicles. Unfortunately, there were insufficient data to explore the effect of secondary air and the frequency of lean high temperature excursions on deterioration. The most recent model year contained in the surveillance data is 1983; the 80+ and 81+ categories include data on the performance of vehicles through the 1983 model year. The sample sizes were generally small, less than 50 vehicles for most of the categories. Linear regressions were generated by pollutant for each category. There was no weighting of the data to account for production volumes; the regressions and sample sizes are displayed in Appendix A. Emission levels were estimated at 4,000 and 50,000 miles by pollutant and technology category from the regressions.

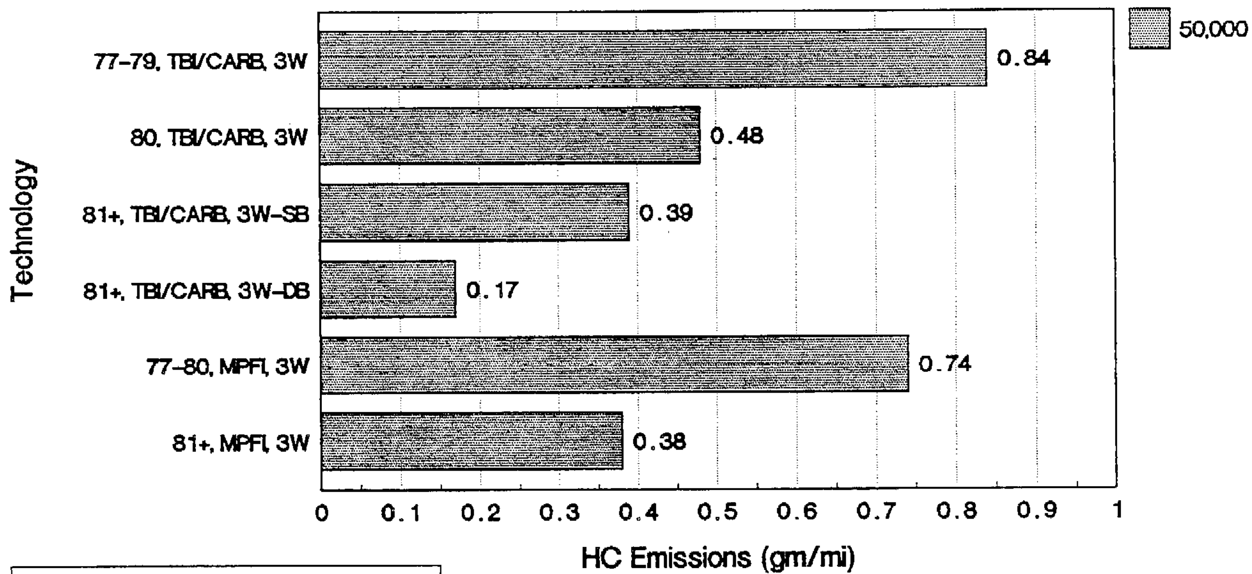
The emission levels of certification vehicles were taken from the annual EPA publication of Federal Certification Results. Sierra maintains an in-house computerized listing of all certified vehicles. The selection of 50,000 mile emission levels and related deterioration rates was simplified by organizing each of the vehicles in the technology categories together by model year. Certification values were selected for vehicles that were either certified in California or for sale in both California and the rest of the U.S. (i.e., 50-state vehicles). The data were averaged, again with no weighting to account for production volumes, to produce emission rates at mileages comparable to the well-maintained in-use vehicle data. A summary of those calculations is presented in Appendix B.

Differences between the data sets are organized by pollutant and displayed in two formats: the first compares the difference or deterioration in emissions at 50,000 miles; the second compares the certification standard to the in-use emission level at 50,000 miles. The latter format is used to provide a perspective on the actual emission levels because even though the deterioration may be substantial in some cases, it is not enough to exceed the standard. The 4,000 mile level differences have not been displayed, because they are larger than would be expected and are considered to be an artifact of the regression used to estimate the in-use vehicle emission levels. Most of the vehicles included in the surveillance data set have mileages in the 20,000 to 50,000 mile range. The 4,000 mile levels are not considered representative of levels emitted by these vehicles. The 50,000 mile differences, however, are believed for the same reasons to be representative of actual deterioration.

Figure 5-1 provides a summary of both formats for HC emission levels. It shows a wide range of deterioration, between 0.17 and 0.84 gms/mi. With the exception of the 81+ TBI/CARB DB TWC systems the deterioration levels are uniformly high, particularly when compared to the HC standard of .41 gm/mi that all of the systems were designed to achieve. As shown in Figure 5-2, all of the technologies exhibit emission levels above the standard at 50,000 miles. The earlier TBI/CARB and MPFI systems both show higher levels of emissions than the later systems. The later MPFI systems do not exhibit a significant improvement in performance over later single-bed TBI/CARB

Figure 5-1

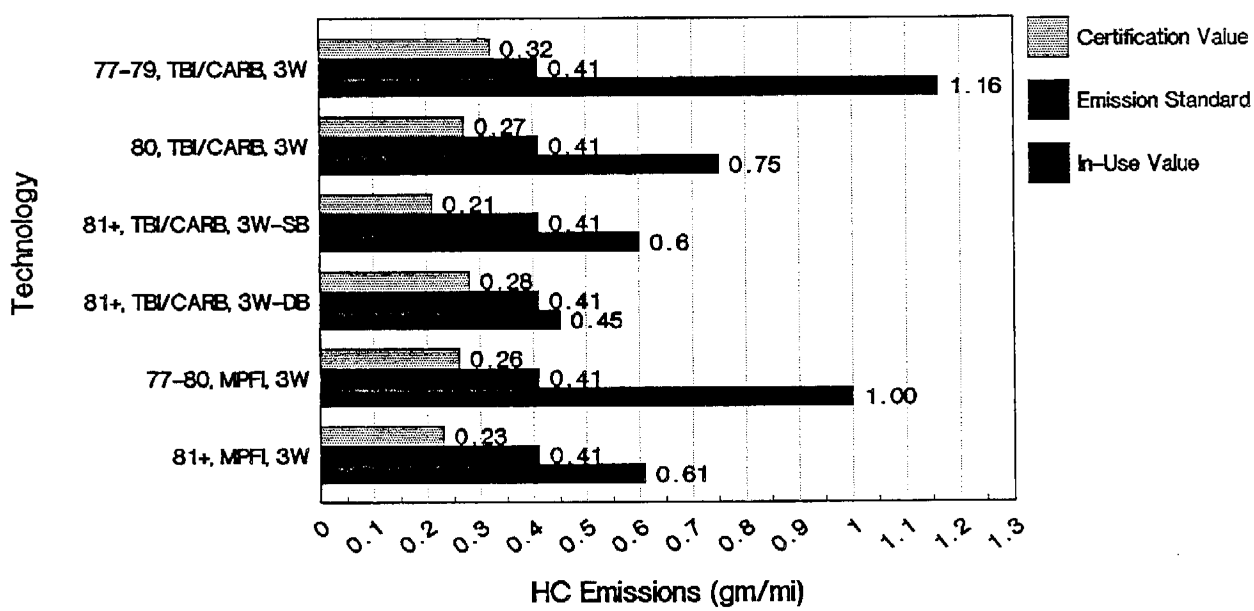
Deterioration in HC Levels Experienced By Alternative Emission Control Systems at 50,000 miles



Deterioration is the difference between average certification and "well maintained" emission levels.

Figure 5-2

Comparison of HC Emission Standard with Certification and In-Use Levels at 50,000 miles for Alternative Emission Control Systems



systems. Unfortunately, the superior performance of the dual bed system holds little value for future vehicle fleets because the trend in emission control systems is away from that design.

Figure 5-3 provides a summary of the emission control system forecasts, developed by EEA, for California vehicles in 1985. It shows a steady shift away from carburetion towards MPFI and TBI systems, but indicates that closed loop carburetors will retain a significant share of the market in 1990. The trend towards single-bed three-way catalysts and the shift away from secondary air is more pronounced. Data presented by EPA in the MOBILE4 workshops suggest a much more rapid shift towards fuel injection in the near term. Their projections show that fuel injection will command almost 90 percent of the market by 1990 and that the MPFI market share will increase rapidly. These projections indicate that the performance of late model TBI and MPFI single bed systems should be reviewed carefully.

Late-model MPFI systems, while demonstrating improvement relative to earlier systems, have in-use HC emission levels that are almost 50 percent above the standard at 50,000 miles. The late-model TBI/CARB SB systems exhibit an almost identical level of performance. This level of degradation is not encouraging for the performance of future vehicle fleets.

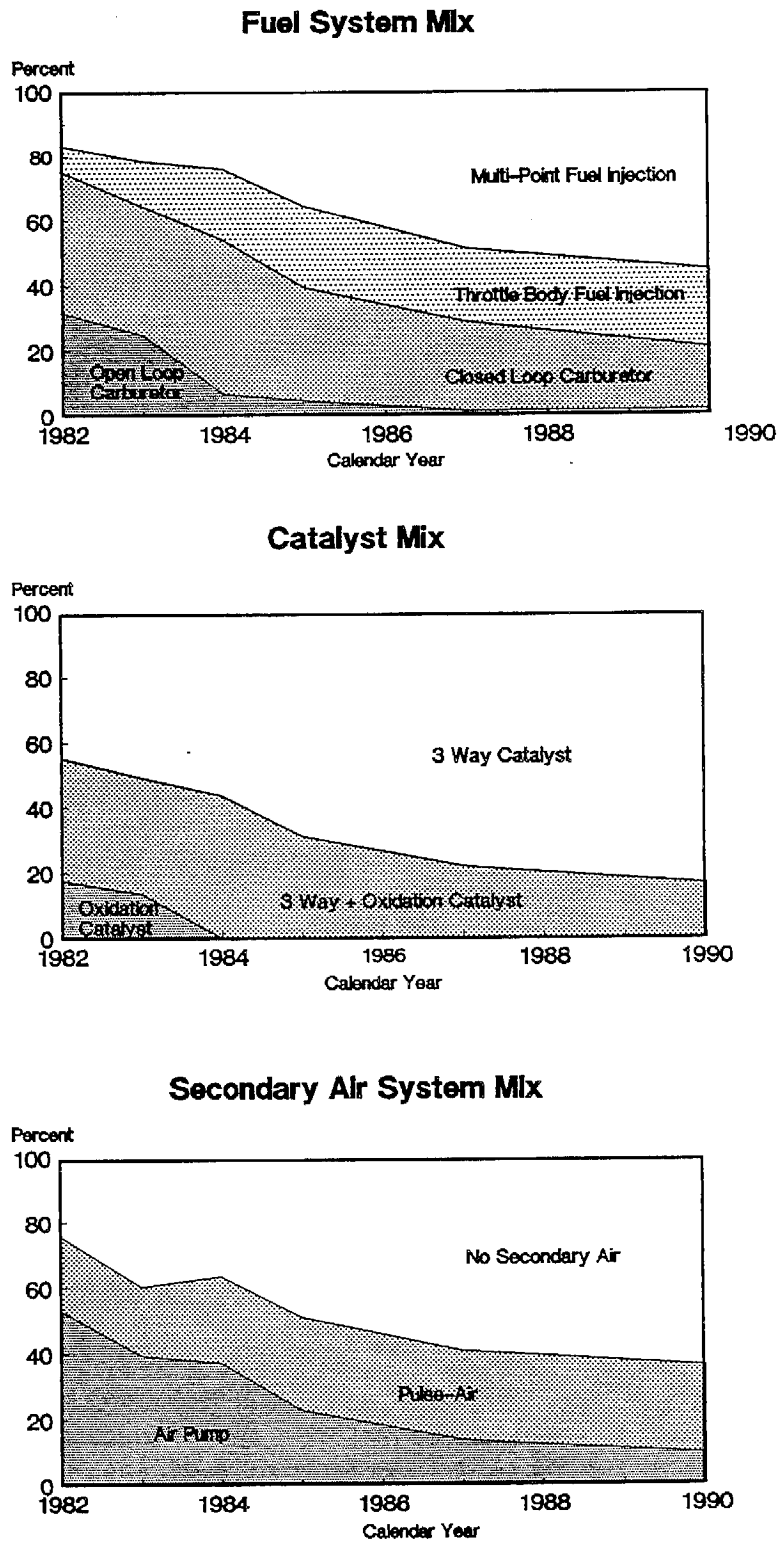
Figures 5-4 and 5-5 display the CO deterioration that the individual technology categories have experienced. The technologies displaying high levels of HC deterioration exhibit similar problems for CO. The early MPFI and TBI/CARB systems both exhibit deterioration on the order of 9 gms/mi at 50,000 miles; both categories are well above their certification standards. The early MPFI systems are approximately 70 percent above the standard.

Determining the performance of 81+ systems relative to certification levels is difficult because two separate CO standards are included in the category: 3.4 and 7.0 gm/mi. The 81+ dual-bed systems again have the lowest levels of deterioration and the lowest in-use emission levels. The late-model MPFI and TBI/CARB single-bed systems again have similar levels of deterioration. The low certification level of the 81+ MPFI system allows it to achieve an improvement in in-use CO relative to the TBI/CARB system.

Figures 5-6 and 5-7 display the NOx deterioration that was experienced by the separate technology categories. It shows that the MPFI systems generally have higher levels of deterioration than any of the other systems. From the perspective of catalyst deterioration this is surprising, because the review of thermal degradation suggested that MPFI system designs minimize the level and frequency of high temperature exceedances. The higher NOx deterioration levels of the MPFI systems indicate Rh sintering and interactions with alumina. Because Rh has the lowest threshold temperature for these mechanisms, it suggests that high temperature excursions may be the cause of the increased NOx. Despite the high levels of deterioration, both MPFI

Figure 5-3

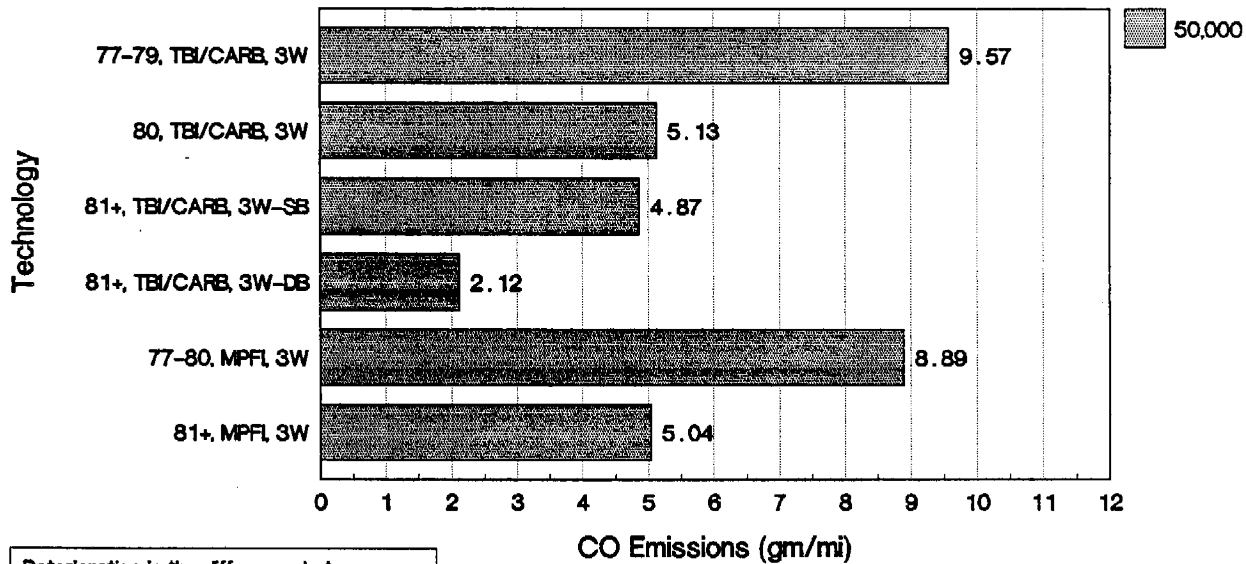
Emission Control System Forecast



Source: R. Crawford, et. al., (1985). Mobile Source Emissions Analysis For Calif., CARB, Contract No. A2-065-32

Figure 5–4

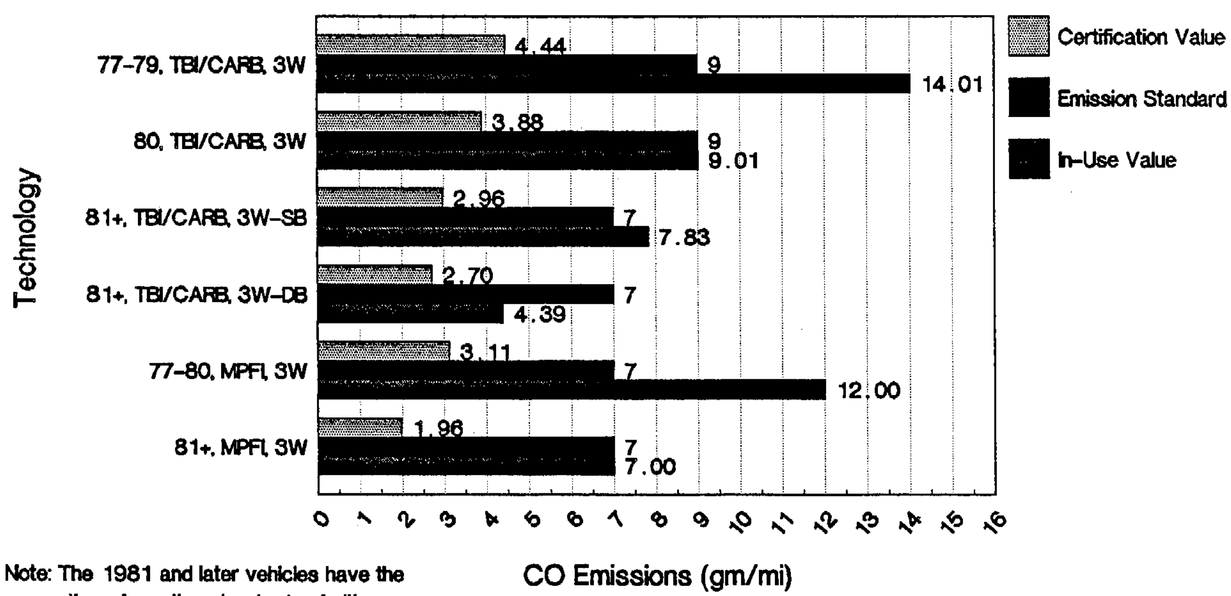
Deterioration in CO Levels Experienced By Alternative Emission Control Systems at 50,000 miles



Deterioration is the difference between average certification and "well maintained" emission levels.

Figure 5–5

Comparison of CO Emission Standards with Certification and In-Use Levels at 50,000 miles for Alternative Emission Control Systems



Note: The 1981 and later vehicles have the option of meeting standards of either 3.4 or 7.0 gm/mi.

Figure 5-6

Deterioration in NOx Levels Experienced By Alternative Emission Control Systems at 50,000 miles

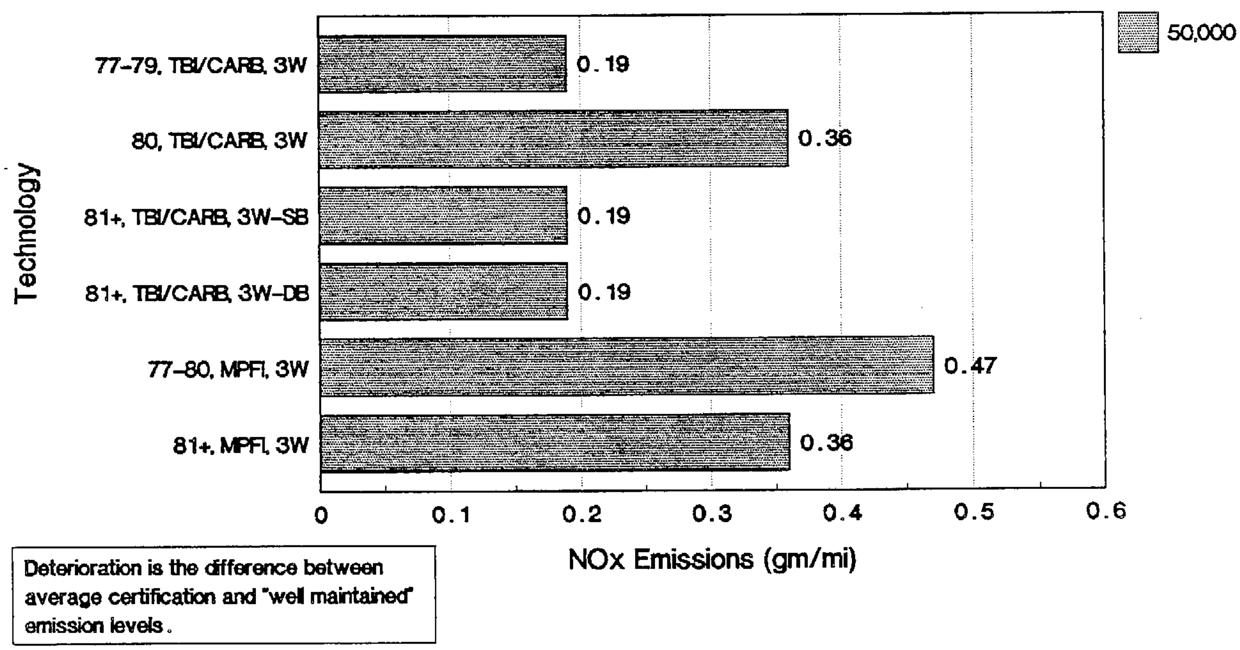
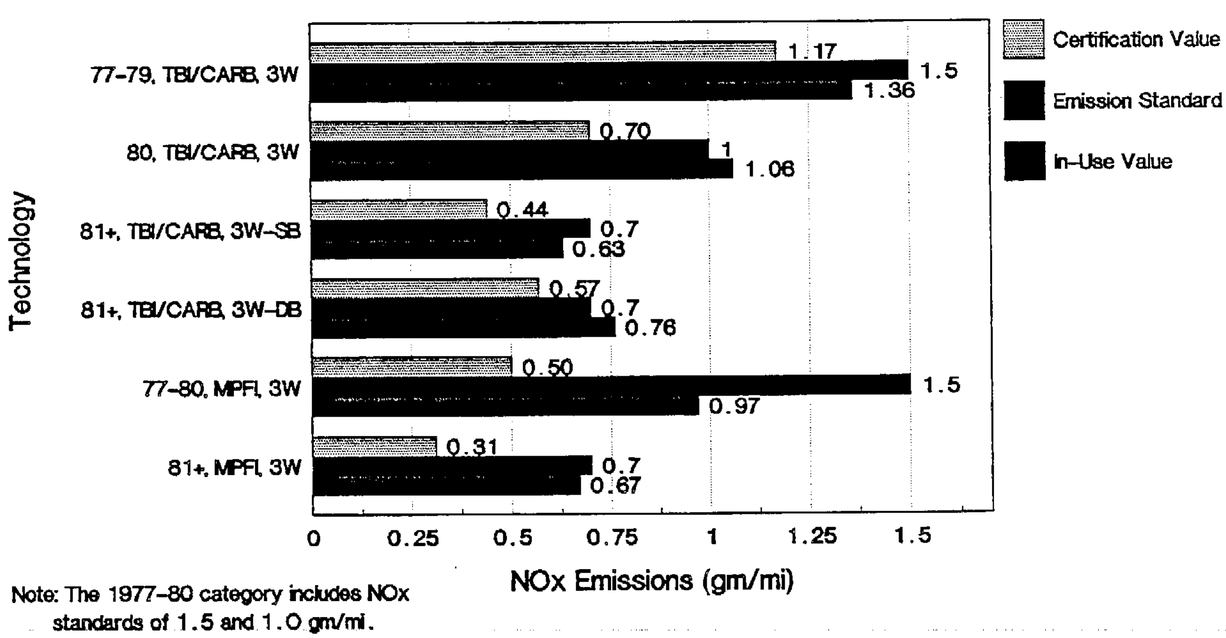


Figure 5-7

Comparison of NOx Emission Standards With Certification and In-Use Levels at 50,000 miles for Alternative Emission Control Systems



system categories achieved in-use NOx levels at 50,000 miles that were below their respective standards.

In general, NOx deterioration does not lead to exceedances of the certification standards. The percentage increase above the certification levels, however, is substantial.

The preceding findings are somewhat surprising in that the review of thermal degradation suggested that CO and NOx would have the highest level of degradation. The data show that there is consistent deterioration between HC and CO, not the distinction that might have been expected if thermal excursions were responsible for the bulk of deterioration.

5.2 Contribution of Deterioration to the Automobile Emissions Inventory

To provide a perspective on the deterioration levels presented, their share of the automobile emissions inventory in the year 2000 has been estimated. Many simplifying assumptions were used to generate this estimate:

- Only the deterioration rates of the 81+ MPFI systems were used, as these systems are considered to be representative of future vehicle fleets.

- The deterioration rates at 50,000 miles were assumed to be representative of the average difference that all vehicles at all odometer levels would experience. As a check, a spreadsheet calculation was used to determine the weighted average odometer reading of the automobile fleet using registration and VMT by age to weight odometer levels. The result was a weighted average odometer level of 57,617 miles. The source of the data for the calculation was EMFAC7D, a summary of the calculation is presented in Appendix C.

- The statewide VMT levels in 2000[3], generated by BURDEN, were multiplied times the deterioration levels of the three pollutants.

- The automobile emission inventory shown for the state is based on a BURDEN run that includes the benefits of an I/M program.

The results are displayed in Figure 5-8. It shows that the HC and CO deterioration of in-use vehicles is responsible for 70 plus percent of the automobile inventory. The NOx deterioration is responsible for roughly 50 percent of the inventory. The magnitude of the estimates may be misleading in that future vehicles will be certifying to tighter standards than the 81+ MPFI vehicle category. However, a review of the deterioration levels of past technologies suggests that the magnitudes of those experienced by the 81+ MPFI systems may be representative of the performance systems. <u>The significance of the</u>

Figure 5-8

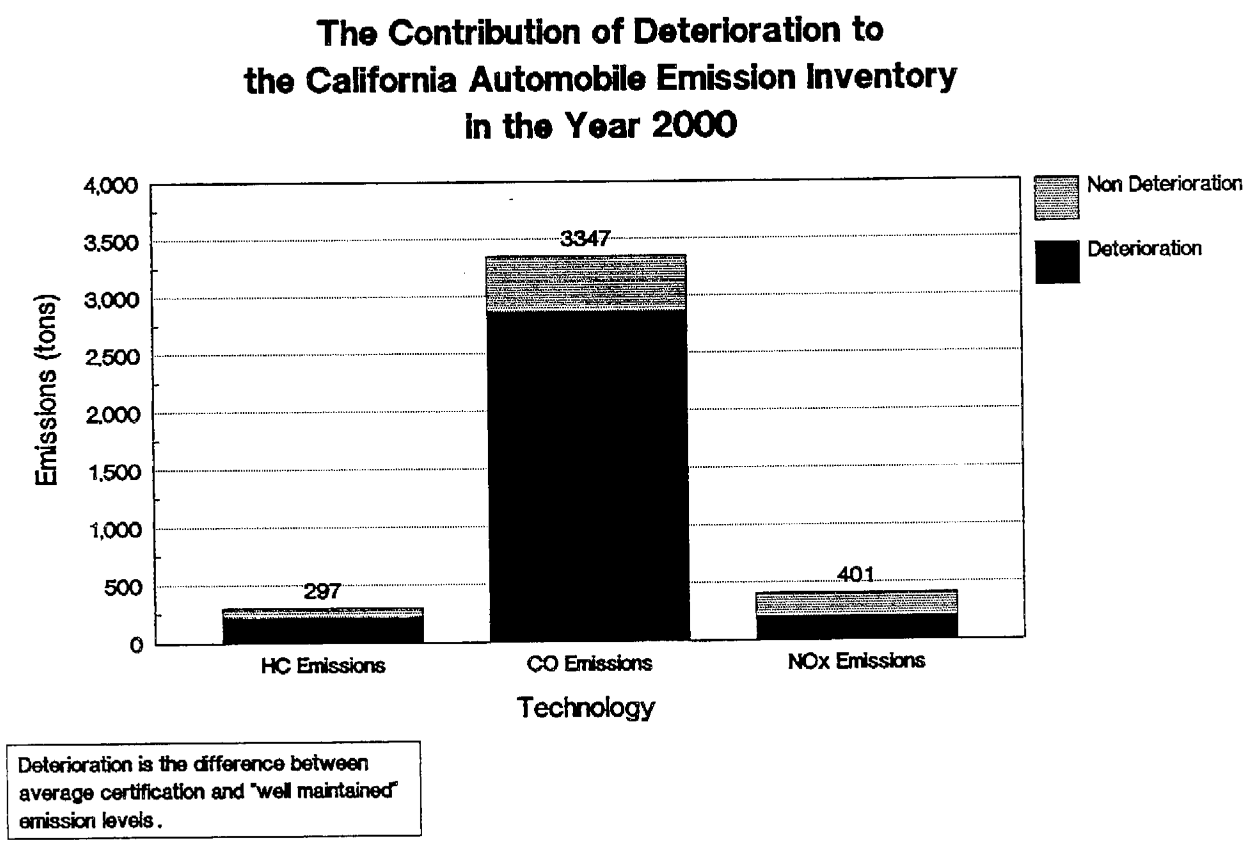


chart is that the difference between emission levels produced by certification vehicles and vehicles operating under in-use conditions is responsible for a major portion of the inventory.

5.3 Summary and Conclusions

It is difficult to discern trends in catalyst deterioration by comparing the performance of in-use and certification vehicles unless it can be assumed that there is no increase in engine out emission levels over the first 50,000 miles of operation. Sierra believes that because most late-model vehicles have closed loop systems and that oxygen sensors are sensitive to chemical and thermal degradation, this assumption cannot be supported. Additional concerns about the effect of ignition and injection system problems also make it difficult to support this assumption. Despite the inability to distinguish between the contributions of catalyst deterioration and engine out emission increases to deterioration, the computed differences between certification and non-tampered in-use vehicles emissions are useful.

In reviewing those results it is important to remember that MPFI systems with single-bed catalysts are projected to be the predominant technology used on future automobiles. The role of Rh in the performance of these systems is critical not only to NOx control but also to the control of HC and CO. With this background, the following conclusions can be drawn:

- From the perspective of percentage and absolute grams per mile increases, CO had the highest level of deterioration. Despite the high levels of deterioration, several of the technologies had in-use emission levels either below or near their certification standards.

- From the perspective of in-use exceedances of the certification standards, HC had the highest level of deterioration. Every one of the technology categories had in-use 50,000 mile levels above the .41 gm/mi standard.

- NOx exhibited the lowest level of deterioration of all of the pollutants; exceedances of the certification standards were negligible. The highest deterioration levels were recorded by late-model single-bed MPFI systems, indicating possible thermal degradation of Rh.

- The ability of in-use vehicles to approach certification standards despite high levels of deterioration, particularly for CO, confirms that manufacturers purposely design vehicles to account for differences between certification and in-use driving conditions. This indicates that the certification program does not subject vehicles to test conditions that are representative of in-use driving experience.

- The technology with the lowest level of deterioration and in-use emission performance was the 81+ TBI/CARB three-way dual bed system. Unfortunately, single-bed systems are projected to be the dominant catalyst design.

- In general, the deterioration levels of 81+ MPFI systems are not substantially different from those of other technologies. An analysis of their contribution to the emissions inventory in the year 2000, when they are projected to be the dominant technology, indicates that <u>deterioration will be responsible for over 70 percent of the HC and CO, and 50 percent of the NOx automobile emissions inventory</u>.

- Improvements to the certification program must be developed to reduce the contribution of deterioration to the emissions inventory.

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LIST OF ABBREVIATIONS

ARB	California Air Resources Board
AMA	Automobile Manufacturers' Association
°C	Degrees Centigrade
CARB	Carburettor
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRC	Coordinating Research Council
DB	Dual Bed
EPA	United States Environmental Protection Agency
°F	Degrees Farenheit
FTP	Federal Test Procedure
gm	Grams
gm/gal	Grams per Gallon
gm/mi	Grams per Mile
HC	Hydrocarbon
H_2S	Hydrogen Sulfide
I/M	Inspection and Maintenance
mg/gal	Milligrams per Gallon
mi/day	Miles per Day
MMT	Methylcyclopentadienyl Manganese Tricarbonyl
Mn	Manganese
M/P	Alkaline Metal/Phosphorus Ratio
MPFI	Multi-point Fuel Injection
MPG	Miles Per Gallon
MVMA	Motor Vehicle Manufacturers Association
NOx	Nitrogen Oxides
P	Phosphorus
Pb	Lead
PCV	Positive Crankcase Ventilation
Pd	Paladium
Pt	Platinum
Rh	Rhodium
RVP	Reid Vapor Pressure
S	Sulfur
SB	Single Bed
Si	Silicon
TBI	Throttle Body Fuel Injection
TWC	Three-Way Catalyst
VMT	Vehicle Miles Travelled
WOT	Wide Open Throttle
ZDP	Zinc Dialkyldithiophosphates
Zn	Zinc

APPENDICES

APPENDIX A

Emission Factors For Well Maintained California Cars (No Tampering)

Technology	Regression	Sample Size
77-79 TBI/CARB 3W	HC = .53 + .13x CO = 5.38 + 1.73x NOx = 1.36 + 0.00x	13
80 TBI/CARB 3W	HC = .35 + .08x CO = 6.19 + .56x NOx = .84 + .04x	57
81+ TBI/CARB, 3W-SB	HC = .27 + .07x CO = 4.92 + .58x NOx = .44 + .04x	29
81+ TBI/CARB, 3W-DB	HC = .30 + .03x CO = 4.39 + 0.00x NOx = .75 + 0.00x	50
77-80 MPFI, 3W	HC = .37 + .12x CO = 4.57 + 1.49x NOx = .97 + 0.00x	24
81+ MPFI, 3W	HC = .36 + .05x CO = 3.42 + .72x NOx = .54 + .03x	41

Note: Data contained in the 1st-8th Surveillance Programs were used to develop the above regressions.

APPENDIX B

Average Certification Values and Deterioration Rates For 50 State and California Vehicles

Technology	Average 50,000 Value		Average Deterioration Rate*	Sample Size
77-79 TBI/CARB 3W	HC	.32	1.206	7
	CO	4.44	1.207	
	NOx	1.17	1.136	
80 TBI/CARB 3W	HC	.27	1.332	18
	CO	3.88	1.270	
	NOx	.70	1.150	
81+ TBI/CARB 3W-SB	HC	.21	1.179	46
	CO	2.96	1.233	
	NOx	.44	1.126	
81+ TBI/CARB 3W-DB	HC	.28	1.260	91
	CO	2.70	1.190	
	NOx	.57	1.082	
77-80 MPFI, 3W	HC	.26	1.15	42
	CO	3.11	1.20	
	NOx	.50	1.16	
81+ MPFI, 3W	HC	.23	1.137	117
	CO	1.96	1.148	
	NOx	.31	1.130	

* Deterioration = The difference between 4,000 and 50,000 miles.

APPENDIX C

Estimate of Weighted Average Odometer For California Vehicles

Age	Annual VMT	Regist. Mix	Weighted VMT	Percent VMT	Odom.	Weighted Odom.
0	15900	0.015	234.53	0.023	3000	70.4
1	15900	0.059	936.19	0.094	13000	1217.2
2	15000	0.069	1042.35	0.104	27200	2835.6
3	14000	0.075	1046.92	0.105	38700	4052.1
4	13100	0.076	998.88	0.100	48500	4845.2
5	12200	0.075	911.46	0.091	56800	5177.8
6	11300	0.070	787.72	0.079	64800	5105.2
7	10300	0.067	687.01	0.069	71720	4927.9
8	9400	0.064	600.75	0.060	76300	4584.4
9	8500	0.061	517.99	0.052	80800	4185.9
10	7600	0.057	433.58	0.043	84500	3664.3
11	6700	0.054	364.55	0.036	87800	3201.2
12	6600	0.049	324.06	0.032	90500	2933.2
13	6200	0.041	255.50	0.026	93000	2376.5
14	5900	0.034	200.60	0.020	95400	1914.0
15	5500	0.031	169.73	0.017	97700	1658.5
16	5100	0.024	123.68	0.012	100000	1236.9
17	5000	0.019	93.40	0.009	100000	934.1
18	4700	0.014	65.94	0.007	100000	659.5
19	4400	0.010	42.24	0.004	100000	422.5
20	4400	0.007	31.46	0.003	100000	314.6
21	4400	0.006	26.40	0.003	100000	264.0
22	4400	0.006	25.92	0.003	100000	259.2
23	4400	0.006	25.92	0.003	100000	259.2
24	4400	0.006	25.92	0.003	100000	259.2
25	4400	0.006	25.92	0.003	100000	259.2
Total		1.000	9998.60	1		57617.9

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°C	Degrees Centigrade
CARB	Carburettor
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRC	Coordinating Research Council
DB	Dual Bed
EPA	United States Environmental Protection Agency
°F	Degrees Farenheit
FTP	Federal Test Procedure
gm	Grams
gm/gal	Grams per Gallon
gm/mi	Grams per Mile
HC	Hydrocarbon
H_2S	Hydrogen Sulfide
I/M	Inspection and Maintenance
mg/gal	Milligrams per Gallon
mi/day	Miles per Day
MMT	Methylcyclopentadienyl Manganese Tricarbonyl
Mn	Manganese
M/P	Alkaline Metal/Phosphorus Ratio
MPFI	Multi-point Fuel Injection
MPG	Miles Per Gallon
MVMA	Motor Vehicle Manufacturers Association
NOx	Nitrogen Oxides
P	Phosphorus
Pb	Lead
PCV	Positive Crankcase Ventilation
Pd	Paladium
Pt	Platinum
Rh	Rhodium
RVP	Reid Vapor Pressure
S	Sulfur
SB	Single Bed
Si	Silicon
TBI	Throttle Body Fuel Injection
TWC	Three-Way Catalyst
VMT	Vehicle Miles Travelled
WOT	Wide Open Throttle
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